

OFFICE OF THE
MINISTER FOR SCIENCE

IRRIGATION IN GREAT BRITAIN

*A Report by the Natural Resources
(Technical) Committee*

LONDON
HER MAJESTY'S STATIONERY OFFICE
1962

NATIONAL RESOURCES (TECHNICAL) COMMITTEE

COMMITTEE ON AGRICULTURE

F. YATES, Sc.D., F.R.S. (*Chairman*)

Deputy Director and Head of Department of Statistics, Rothamsted Experimental Station, Harpenden, Hertfordshire.

A. A. BINDLOSS, B.Sc. (Agric.) Dip. Agric.

Unilever Limited, Unilever House, London, E.C.4.

E. BRUNDRETT, O.B.E.

Acton Farm, Charing, Ashford, Kent.

Professor M. M. COOPER, A.Agr.Sc.(N.Z.), B.Litt.(Oxon), Dip.Rur.Econ. (Oxon), F.R.S.E., (Dean of Agriculture)

Kings College, Newcastle.

E. G. COX, T.D., D.Sc., F.Inst.P., F.R.I.C., F.R.S.

Secretary, Agricultural Research Council.

W. DAVIES, D.Sc.

Director, Grassland Research Institute, Hurley, near Maidenhead, Berkshire.

Professor W. ELLISON, B.Sc., Ph.D., (Professor of Agriculture (Crop Husbandry))
Institute of Rural Science, University College of Wales, Aberystwyth, Wales.

F. H. GARNER, M.A., M.Sc.

Principal, Royal Agricultural College, Cirencester, Gloucestershire.

Professor W. HOLMES, B.Sc. (Agric.), Ph.D.(Glas.), (Professor of Agriculture)
Wye College, near Ashford, Kent.

Professor J. E. NICHOLS, M.Sc., Ph.D., F.R.S.E., (Professor of Agriculture (Animal Husbandry))

Institute of Rural Science, University College of Wales, Aberystwyth, Wales.

Dr. O. T. W. PRICE, B.Sc., M.S.(Wisconsin), M.A., D.Phil.(Oxon)

I.C.I. Limited, Billingham, Co. Durham.

Professor J. R. RAEBURN, B.Sc.(Agric.), Ph.D., M.S., F.R.S.E., (Professor of Agriculture)

Marischal College, Aberdeen University.

D. B. WALLACE, M.A.(Cantab)

Farm Economics Branch, School of Agriculture, University of Cambridge.

Sir SOLLY ZUCKERMAN, C.B., F.R.S.

Ministry of Defence, Storey's Gate, London, S.W.1.

J. R. U. PAGE; D. L. SIMMS: *Secretaries*.



Study Group on Irrigation

- F. H. GARNER, M.A., M.Sc., (*Chairman*)
Principal, Royal Agricultural College, Cirencester, Gloucestershire.
- *C. CULPIN, O.B.E., M.A., Dip.Agric.(Cantab.), M.I.Agr.E.
Chief Machinery Adviser, National Agricultural Advisory Service,
Institute of Agricultural Engineering, Silsoe, Bedfordshire.
- W. ELLISON, B.Sc., Ph.D., (Professor of Agriculture, (Crop Husbandry))
Institute of Rural Science, University College of Wales, Aberystwyth,
Wales.
- *E. A. G. JOHNSON, C.B.E., B.Sc.(Eng.) M.I.C.E., M.I.W.E.
Chief Engineer, Land Drainage and Water Supply Division, Ministry
of Agriculture, London, S.W.1.
- J. S. NIX, M.A., B.Sc., (Econ.)
Farm Economics Branch, School of Agriculture, University of
Cambridge.
- *J. J. NORTH, B.Sc., M.S., Dip.Agric.
National Agricultural Advisory Service, West Midlands Region,
Wolverhampton, Staffordshire.
- H. L. PENMAN, M.Sc., Ph.D., F.Inst.P., F.R.S.
Head of Physics Department, Rothamsted Experimental Station,
Harpenden, Hertfordshire.
- *C. N. PRICKEIT, A.M.I.C.E.
Engineer, Land Drainage and Water Supply Division, Ministry of
Agriculture, London, S.W.1.
- W. S. ROGERS, M.A., Ph.D., D.Sc.
Head of Pomology Section, East Malling Research Station, East
Malling, Kent.
- F. A. SECRETT, C.B.E., F.L.S., V.M.H.
Director, F.A. Secrett Limited, Hurst Farm, Milford, Surrey.
- *L. P. SMITH, B.A.
Meteorological Office, Bracknell, Berkshire.
- R. S. TAYLER, B.Sc., Dip.Agric., N.D.A.
The University, Reading, Berkshire.
- T. E. WILLIAMS, B.Sc.
Deputy Director, Grassland Research Institute, Hurley, Berkshire.
- E. J. WINTER, M.C., M.Sc.
Head of Irrigation Section, National Vegetable Research Station,
Wellesbourne, Warwickshire.
- C. S. WRIGHT, M.I.Agr.E.
Director, Wright Rain Limited, Crowe, Hampshire.
- D. L. SIMMS, B.Sc., A.Inst.P., *Secretary*
- OFFICE OF THE MINISTER FOR SCIENCE,
Whitehall, London, S.W.1.

*Assessor to the Study Group.

FOREWORD

THIS report has been prepared by a Study Group for the Committee on Agriculture of the Natural Resources (Technical) Committee. The Natural Resources (Technical) Committee was constituted in 1950 to advise on the technical problems of the development, use and conservation of the natural resources of the United Kingdom.

Recently there has been growing concern with the need to conserve more effectively and utilise more efficiently the limited water sources of this country. Concurrently the use of irrigation has been spreading, and this is now making considerable demands on the available water supplies in certain areas. The present report examines the possibilities and consequences of irrigation in this country. It brings together the available information on crop responses, costs and returns, and assesses the likely value of irrigation to the farmer and to the community. Tentative estimates are made of the potential demands for water for irrigation. The study has also served to bring to light the present gaps in our knowledge of the subject.

F. YATES

Chairman of Committee on Agriculture

February, 1962.

CONTENTS

	PAGE
Abstract	1
Section 1. Introduction	4
Section 2. Basic Information	6
2.1 <i>Why irrigate?</i>	6
2.1.1 Water and growth	6
2.1.2 Soil water—and some technical terms	6
2.1.3 Potential transpiration rate	8
2.1.4 Variability of rainfall	8
2.1.5 Frequency of irrigation need	9
2.2 <i>Basic effects</i>	10
2.2.1 Rates and amounts	10
2.2.2 Need for drainage	14
2.3 <i>Guides to irrigation need</i>	14
2.3.1 Water-balance sheet	14
2.3.2 Tension measurements (direct and indirect)	15
2.3.3 When to irrigate	15
Section 3. Water Supplies	17
3.1 <i>Sources of water</i>	17
3.2 <i>Present methods of supply</i>	17
3.3 <i>Methods of increasing supplies</i>	19
3.3.1 Surface water storage	19
3.3.2 Ground water storage	20
3.3.3 Planning and co-ordination	20
Section 4. Methods	21
4.1 <i>Methods</i>	21
4.2 <i>Sub-surface irrigation</i>	21
4.3 <i>Surface irrigation</i>	21
4.3.1 Limitations of surface methods	21
4.4 <i>Overhead irrigation</i>	21
4.4.1 Equipment	21
4.4.2 Types of system	22
4.4.3 Advantages of overhead irrigation	23
4.4.4 Limitations of overhead irrigation	23
Section 5. Costs	24
5.1 <i>Operating costs</i>	24
5.1.1 Average costs	24
5.1.2 Range in costs	24
5.1.3 Fixed costs	24
5.1.4 Running costs	26
5.2 <i>Capital costs</i>	27
5.2.1 Source works	27
5.2.2 Distribution equipment	29
5.2.3 Capital costs on the individual farm	31
Section 6. Response of Crops	33
6.1 <i>General</i>	33

	PAGE
6.2 <i>Farm crops</i>	34
6.2.1 Potatoes	34
6.2.2 Sugar beet	36
6.2.3 Cereals	37
6.2.4 Field beans	37
6.3 <i>Grassland</i>	38
6.3.1 Techniques	38
6.3.2 Response	38
6.3.3 Other benefits	39
6.3.4 Utilization experiments	40
6.4 <i>Fruit</i>	40
6.4.1 Tree fruits	41
6.4.2 Small fruits	42
6.5 <i>Vegetables</i>	43
6.5.1 General	43
6.5.2 Examples	44
6.5.3 Response	45
6.6 <i>Other aspects</i>	46
6.6.1 Protection against frost	46
6.6.2 Irrigation and fertilizer practice	47
6.6.3 Spreading fertilizers	48
6.6.4 Disposal of animal manure	48
6.6.5 Pests and diseases	48
6.6.6 Quality of water	48
Section 7. Economics of Irrigation	51
7.1 <i>The individual farmer</i>	51
7.1.1 General	51
7.1.2 Financial returns	51
7.1.3 Priorities	53
7.1.4 Other benefits	54
7.2 <i>Effects on farm management</i>	54
7.2.1 General	54
7.2.2 Grassland	55
7.3 <i>Broader aspects</i>	55
Section 8. The Demand for Water	57
8.1 <i>General</i>	57
8.2 <i>Present demands and rates of increase</i>	57
8.3 <i>Theoretical limit of development</i>	59
8.4 <i>Practical limit of development</i>	59
8.4.1 Method of calculation; England and Wales	60
8.4.2 Method of calculation; hydrometric areas	62
8.5 <i>Discussion</i>	63
Section 9. Problems for Further Study	67
9.1 <i>General</i>	67
9.2 <i>Provision of water</i>	67
9.3 <i>Crop responses and the efficient utilization of water</i>	68
9.4 <i>Grassland problems</i>	69

	PAGE
9.5 <i>Economics</i>	69
9.6 <i>Application of water</i>	69
9.7 <i>Organization of research and development</i>	69
Section 10. Summary and Recommendations	71
10.1 <i>Irrigation need</i>	71
10.2 <i>Methods</i>	71
10.3 <i>Sources of water</i>	72
10.4 <i>Costs</i>	73
10.5 <i>Response of crops</i>	73
10.6 <i>Returns</i>	74
10.7 <i>Demand for water</i>	75
10.8 <i>Research problems</i>	75
10.9 <i>Recommendations</i>	75

APPENDICES

APPENDIX A Calendar of irrigation need	77
B Acreages likely to be irrigated	79
C Problems for further study	81

FIGURES

FIGURE 1 Frequency of irrigation need (General)	11
2a Frequency of irrigation need (Main crop potatoes during July and August)	12
2b Frequency of irrigation need (New potatoes during May and June)	13

TABLES

TABLE 2.1 Months in which irrigation was needed (1950-59)	9
4.1 Characteristics of overhead irrigation	22
5.1 Average costs per acre-inch (shillings)	25
5.2 Range in costs per acre-inch (shillings)	25
5.3 Variations in fixed costs per acre-inch	26
5.4 Approximate cost of portable main—£	30
5.5 Capital costs at three levels of source work costs—£	32
7.1 Likely responses of crops to irrigation	52
7.2 Total cost of irrigation per acre (shillings)	53
8.1 Estimates of present irrigation development and increases in the next 10 years (Ministry of Agriculture).	58
8.2 Theoretical limit of irrigation development	59
8.3 England and Wales. Practical limit of demand	61
8.4 Size and duration of economic peak daily demands (million gallons per day)	62
8.5 River Great Ouse. Practical limit of demand	64
8.6 River Severn. Practical limit of demand	65

IRRIGATION IN GREAT BRITAIN

ABSTRACT

THIS report, which discusses the effectiveness and value of irrigation in Britain, shows that irrigation of certain crops in parts of Britain can lead to a major increase in productivity; the main problem is to provide water where it is needed, and some ways of meeting this need are discussed.

Many agricultural crops only give their best yield under conditions of plentiful water supply; in many parts of Britain, shortage of water in the soil, due to dry periods in the six summer months, leads to great reductions in crop yield and large differences in yield from year to year. If this water shortage is made good by irrigation, average yields increase and the year to year variation is lessened. Irrigation can reduce unit costs and improve efficiency of production, with benefit to both the irrigation user and the consumer.

The area needing irrigation is roughly those parts of England receiving on average less than 35 inches of rain per year, and of Scotland less than 30 inches. The frequency of need is greatest in the south and east, being about 9 years in 10 around the Thames Estuary, decreasing north-westwards towards the higher rainfall areas. About 4 inches* of water per year will make good the shortage except in the very driest years.

Modern irrigation is almost entirely by overhead methods, which are more economical both in water and labour than the older surface (i.e. furrow or flooding) methods. The costs of irrigation vary greatly according to availability of water and equipment required. Capital costs for pumps, pipelines and sprinklers may average about £25 per acre. Running costs plus depreciation and interest may amount to about 45s. per acre-inch for an annual application of 3 inches. If water is charged for, or if source works, such as a dam, reservoir or borehole, are needed, the capital and running costs will be correspondingly higher.

The response of different crops to irrigation depends on their life cycle and root range, as well as on the actual moisture deficiency of the soil; some crops have specially moisture-sensitive periods, others can be profitably irrigated at any time. Broadly speaking, the growth of an irrigated crop is similar to that of a crop grown with ample summer rainfall. By comparison with an un-irrigated crop suffering moisture stress, the irrigated crop shows a greater growth and yield, and often better flavour and quality. Irrigation can also increase ease of sowing and harvesting, and often allows an extra crop to be grown.

Vegetables respond so profitably to irrigation that almost all market gardens are now irrigated to some extent. Potatoes—especially early potatoes—also show a good response in most years. Small fruits, such as strawberries, raspberries and blackcurrants have benefited greatly from irrigation. Fruit trees on deep soil rarely need irrigation but good responses have been found on soils less than 2 feet deep, and with perennial plants such as fruit trees and bushes the response is cumulative. Sugar beet has shown economic responses in dry

*1 acre-inch is equivalent to 22 600 gallons of water.

years. Mean increases of about 40 per cent in yield of dry matter from grass have been obtained by irrigation; fluctuations in yield are reduced, thus increasing efficiency and easing management.

It is difficult to give precise figures for the profitability of irrigation of individual crops, because of the variation in costs and returns under different conditions and the paucity of experimental evidence. High value crops on intensively farmed land benefit most from irrigation. Maincrop potatoes receiving about 4 inches of water may give an increased yield of 3 tons per acre, valued at about £50; cauliflowers, receiving 2 inches, an increase of 3 tons, valued at up to £150; strawberries, raspberries and blackcurrants, receiving 2-4 inches of water an increase of yield of 20 to 50 per cent, valued at between £50 and £100 per acre; apples on shallow soil receiving 3 inches, an increase of about 40 per cent, valued at £100 per acre. Grass may give an increased return of about £20 per acre, from 5 inches of water; here the cost of water is critical. Irrigation of grass can only be recommended if it is intensively utilized.

It is estimated that about 130 000 acres of land are irrigated at present; and the area is increasing by about 15 000 acres per annum. At this rate of expansion, if water can be made available at low cost, about half a million acres might be irrigated by 1980. To apply 4 inches to this area would require 50 000 million gallons. Rough estimates—accurate figures of crop acreages are not at present available—of the eventual practical limits of demand suggest that the area in England and Wales may rise to about $1\frac{1}{2}$ million acres, with a peak annual demand of well over 100 000 million gallons. The peak daily demand may vary by as much as 50 per cent within the season and is likely to be at its maximum in mid-June or July. Estimates for the demands in the hydrometric areas of the Great Ouse and the Severn have also been made.

The water used in irrigation has been obtained from various sources of supply, sometimes—and now increasingly—in competition with other users. The demand varies greatly and is at its highest when supplies are at their lowest. Existing sources, in some areas, are unable to cope with any large increase in demand for water for farm irrigation. Substantial expansion of irrigation is only possible by increased conservation, mainly by storage of winter flow, over and above that needed for public supply purposes. The most immediate practical solution to the supply problem is to conserve water in small units as close as possible to the land which is to be irrigated. Conservation of this kind has already started and is eligible for government grants; but, in the long term, wider conservation of water resources and more comprehensive planning of their use will be needed. As the demand for water grows, increased precautions may be necessary to prevent polluted water, that might endanger health or damage crops or soils, from being used.

It is clear, both from research and from current practice, that irrigation can produce higher yields and lead to more efficient use of agricultural land. As it can stabilize production and eliminate the risk of crop failure due to drought, it should also lessen variation in prices. All these features are valuable to the irrigation user, the consumer and the nation. It must be recognized, however, that the increasing use of irrigation will cause gradual changes in cropping practice.

The information already available enables the farmer to use irrigation effectively, but there are gaps in the knowledge of the subject. To obtain greatest

efficiency at lowest cost and to utilize the limited water supplies most effectively, further research is needed; some subjects on which more knowledge is needed are listed in the report, together with suggestions for co-ordinating the research work and disseminating the results. Besides research problems, some administrative problems need further examination.

To ensure the best use of available water and the most efficient development of irrigation the following recommendations are made.

RECOMMENDATIONS

1. Because of the benefits to users, consumers, and the nation, the judicious use of irrigation in agriculture and horticulture should be encouraged.

2. After domestic requirements have been satisfied, with provision for garden and amenity uses, the supply of water for irrigation should be considered together with that for industrial purposes. Horticulture should receive priority.

3. Increased conservation of water for irrigation should be encouraged, especially by local storage in small units close to the land to be irrigated. Conservation works should be properly planned in relation to each other and in conjunction with the proper development of the water resources of the whole catchment or other hydrological area.

4. Farm reservoirs, as part of the efficient development of the water resources of an area, must be designed and constructed to high standards, ensuring safety and economy.

5. More research is needed:

- (a) Fundamental—on the water relations of crops, that is, the inter-relationships between plants, soils, and water.
- (b) Technical—on the responses of crops to irrigation and the management of irrigation equipment.
- (c) Operational—to obtain information on current practices. Questions on irrigation should be included in the Agricultural Returns of the Ministry of Agriculture, Fisheries and Food and surveys of irrigation practice should be undertaken.

Consideration should be given to establishing an Irrigation Area and, within it, an Irrigation Research Station or a Ministry of Agriculture Experimental Husbandry Farm designed primarily for fieldwork on irrigation. The Meteorological Research Committee of the Air Ministry should be encouraged to initiate, or accelerate, research on quantitative forecasting of rainfall for periods of three to four days ahead.

6. Irrigation users should have adequate representation on any water controlling authority.

SECTION 1

INTRODUCTION

The idea of Britain being a country in which irrigation is needed is perhaps surprising, although market gardeners are well aware of its necessity and value. Nonetheless, both research and practice have shown that there are very few years in which crops in most of the lowlands would not benefit from additional rain at some time in the growing season.

This report is designed to examine the possibilities and consequences of irrigation on a farm scale in this country. Market gardens are already being extensively irrigated but even here further increases are to be expected.

The following may help to put the present study into context.

The use of irrigation as a farming technique is increasing rapidly, encouraged by grants from the Ministry of Agriculture. Even after a decade that has been wetter than normal, about 130 000 acres are now irrigated, and the area is increasing at the rate of 15 000 acres per annum.* The total capital investment in irrigation can only be estimated, but, on the basis of an average capital cost of £25 per acre, i.e. assuming little or no source work, the total present investment is about £3 million with an annual investment of about three-quarters of a million pounds, whilst the total running costs are about half-a-million pounds assuming that water is available at negligible cost. If the present rate of increase continues these figures will be about doubled in ten years' time. If irrigation spreads rapidly and there is substantial expenditure on source works, the increase may be much greater.

Already the demand for irrigation water in a dry summer, coming as it almost invariably does when supplies are short, causes considerable embarrassment to River Boards and water supply authorities. The sub-Committee on the Growing Demand for Water of the Ministry of Housing and Local Government in its first report^(1,2) found that there was little likelihood of a general shortage of water for all purposes excluding irrigation, but even their preliminary study^(1,2) of the demand for irrigation water convinced them that legislation is necessary to control abstractions of surface water; ground water abstraction is already controlled.

There is increased consciousness of the need to conserve, and utilize effectively, the water resources of this country. Legislation on flood control and pollution prevention have been features of recent sessions of Parliament. Plans for more far reaching water conservation and control are expected shortly.

The Surface Water Survey of the Ministry of Housing and Local Government are undertaking a hydrological survey of the country's water resources, area by area, in which the resources and demands, both present and potential, are assessed: three surveys, the River Great

*See page 57.

Ouse^(1.3), the River Severn^(1.4) and the Essex Rivers and Stour^(1.5), have so far been published. The Welsh Advisory Water Committee have published a report on the Water Resources of Wales^(1.6).

The demand for irrigation water must be considered in relation to available supplies and the cost of providing new supplies, and has to be compared with the competing demands for public and industrial purposes. An assessment of the value of irrigation, both to the individual farmer and to agriculture as a whole, is therefore necessary to provide the basis for such comparisons. Because practical experience is inadequate, and research programmes are incomplete, there are serious gaps in the information that cannot be filled immediately, but sufficient is already known of the basic principles and benefits of irrigation to make a study worth while. The important questions to be answered are "What are the effects of irrigation on crops?" "Does it pay?" "Does it justify its demands on the country's water resources?"

Some soil-water-plant relationships are stated to demonstrate the need for irrigation as a supplement to summer rainfall, and provide a basis for estimating where and when the need arises in Britain. The present water supply situation, and the most likely sources of water for irrigation are considered. Methods of irrigation and their cost are then discussed in terms of sources of water and types of equipment. Present knowledge of the way crops respond to irrigation, including the timing of irrigation and the effects of yield, flavour and quality, is summarized. On the basis of this information, costs and returns are compared, enabling crop priorities to be considered in terms of the limited supply of water available. The economic aspects of irrigation for the individual farmer, and the impact a greater use of irrigation might have on the nation's agricultural policy are then assessed. The way in which the demand for water may increase in the near future is then examined, and an attempt is made to forecast the practical limit of demand; such forecasts are necessarily very tentative, and will improve as experience accumulates. Further research needs to be undertaken.

REFERENCES

- 1.1 Central Advisory Water Committee (1959). *Sub-committee on the Growing Demand for Water: First report.* (S.O. 75-65) H.M.S.O., London.
- 1.2 *ibid.* (1960) *Sub-committee on the Growing Demand for Water: Second Report:* (S.O. 75-9999) H.M.S.O., London.
- 1.3 *Hydrological Survey 1960, River Great Ouse Basin*, Ministry of Housing and Local Government, H.M.S.O., London.
- 1.4 *ibid.* 1960, River Severn Basin.
- 1.5 *ibid.* 1961, Essex Rivers and Stour.
- 1.6 Welsh Advisory Water Committee (1961) *Report on the Water Resources of Wales.* (Cmd. 1331) H.M.S.O., London.

SECTION 2

BASIC INFORMATION

2.1 WHY IRRIGATE ?

Without water, plant growth is impossible. Within certain limits, increased supplies of water produce increased growth up to a stage at which other factors become limiting, and then extra water produces no benefit and may even be harmful. In semi-arid areas, farming depends almost entirely on irrigation. In semi-humid zones, natural rainfall enables useful crops to be grown in most years, but, in the drier years, the plants cannot respond fully to the good growing conditions provided by abundant sunshine and high temperatures, because water becomes a limiting factor. It is in such areas that the use of supplementary irrigation could be profitable; parts of the British Isles come into this category, and the purpose of this section is to show why they do so, and where they are.

2.1.1 *Water and growth*

Plant growth depends on assimilation of carbon dioxide through minute pores (stomata) on the leaf surfaces. The stomata close if the water content of the leaf is not high enough to maintain turgidity, and hence growth is checked. Conditions that permit maximum stomatal opening also permit maximum rates of evaporation of water through the stomata, but these rates can only be maintained if the water so evaporated is replaced by water from the soil around the plant roots. The suction exerted in the leaves has to overcome a tension in the soil, and the drier the soil the greater the tension, i.e. the more difficult it is to extract further water from it. Thus the water is absorbed from the soil by the roots, transported to the leaves, and then evaporated from them into the free atmosphere. This process is known as *transpiration*. As a broad generalization, for good growth the water content of the leaves must be kept high; and to keep the water content of the leaves high there must be a high water content in the soil. When this condition is satisfied the transpiration rate reaches the full potential rate determined by external factors.

2.1.2 *Soil water—and some technical terms*

Two or three days after thorough wetting, soil drains to an equilibrium (or near equilibrium) state, known as *field capacity*; the quantity of water held and the tension with which it is held varies with soil type. In the cultivated layer of farm soils, the quantity of water might be about 3.5 inches per foot depth, and the tension about 0.1 atmosphere suction. As the soil dries, the quantity decreases and the tension increases, and an important limit is reached when a plant can no longer overcome the tension; the plant then wilts, i.e. the cells lose their turgor (become limp). Temporary wilting may occur under conditions of rapid drying, even when soil water is still available; but a more important limit of soil drying is the *permanent wilting point* at which the plant remains wilted until further moisture is added to the soil, even if the atmosphere

is saturated with water vapour. At this limit, the tension in the parts of the soil around the roots is about 15 atmospheres, and is independent both of the kind of soil and of the agricultural crop. The quantity of water remaining in the soil at this stage does depend on soil type, being about 1.5 inches per foot for an ordinary field soil. The quantity of water taken out between *field capacity* and *permanent wilting point* is known as the *available water*: for the example quoted it would be 2 inches (i.e. 3.5-1.5 inches) per foot depth of soil.

The amount of *available water* that can be held by any particular soil depends largely on the soil texture, but is also affected by the amount of organic matter present. Light sandy soils hold about 1 inch per foot of depth; heavy clay soils about 2 to 2½ inches per foot of depth, and loams are intermediate. Values for sub-soils are usually smaller—often about 1 inch per foot depth.

The amount of water available to a particular crop will depend, of course, on the depth of its rooting, and the available water in each zone of soil occupied. Thus shallow-rooting plants tap smaller soil water reserves than deep-rooting plants on the same soil, and may therefore need irrigating more frequently. For example, grass roots with an effective depth of 2 feet, on a soil containing 2 inches available water in the top foot of soil, and 1 inch per foot depth in the sub-soil, would tap an available water reservoir of 3 inches, while lucerne or fruit tree roots, with an effective depth of 5 feet, on the same soil would tap a water reservoir of 6 inches. The total available water within the root zone of a plant (sometimes called its root reservoir) forms the limit of the plant's water reserves in dry periods, and it is therefore important to know this quantity.

Not only is the total amount of available water held by a soil important, but also the ease with which plants can obtain this water, for the tenacity with which water is held by soil, or the work required, to remove water from soil, is an important factor influencing the plant response to soil moisture conditions. The ease with which plants can obtain the available water depends on the *moisture release characteristics* of the soil. The moisture release curve defines the relationship between moisture content and the tension holding the water in the soil.

Soils of different textures have very different moisture release characteristics, and thus the ease with which plants can obtain the available water differs from soil to soil. For example, a high proportion of the available water of a sandy soil is held at a low tension and is, therefore, readily available to the plant, whilst a heavy type of soil may have only a small proportion of the available water held at a low tension. The amount of organic matter and the soil structure also influence moisture release characteristics. Recent work suggests that these observations concerning water availability may need modifying for certain soil conditions, particularly for soils with high silt content, but their usefulness as a general guide to assessment of water reserves of plants is well established.

The total water extracted by evaporation and transpiration from the soil, less gains by rainfall or irrigation, is termed the *soil moisture deficit*, and is the amount of rain or irrigation that would restore the soil to field capacity, with no surplus for drainage. If less than this amount is added, then only the top part of the soil is brought to field capacity, and the lower part remains dry. It is not possible to produce uniform wetting of a soil profile to any state drier than field capacity.

2.1.3 *Potential transpiration rate*

With a satisfactory soil water regime, and a crop cover that completely shades the ground, the transpiration rate per unit area of ground becomes independent of the soil, and largely independent of the kind of crop. The predominant controlling factor is the weather, and the physics of the relationships has been worked out in sufficient detail—and checked by experiment—to permit the estimation of a *potential transpiration rate* for any region, given the weather data for the region. If in a chosen month, the rainfall is less than the calculated potential transpiration, then a soil moisture deficit will be built up during the month, and for a part of the period the plant will be working against a tension in the soil, possibly with some check to growth. Though the magnitude of the deficit can be estimated with some confidence, its agricultural importance cannot be predicted by any physical reasoning: experience and experiment are needed for this, and much of the present report is a summary of such experience and experiment.

Computation from weather data of potential transpiration is made as if it were from a grass surface. It is possible that for taller crops the value ought to be a little greater (this is one of the main subjects of current research); but, by using the grass figure as a basis for prediction, any estimate of frequency or size of irrigation need will tend to be an under-estimate for crops other than grass. The deficit that needs to be made good is also affected by the completeness of the ground cover, but the correction that has to be made is normally relatively small.

Details have been published⁽¹⁻³⁾ of the computation for sub-counties in England and Wales, month by month, from April to September. The following examples will serve to demonstrate regional contrasts. At East Malling in Kent, the average summer potential transpiration is 17 inches and the average summer rainfall is 12 inches: at Buxton, Derby, the corresponding figures are 14 and 21 inches. Thus Buxton has an average summer surplus of 7 inches, but East Malling has an average summer deficit of 5 inches. This is a theoretical deficit, and some adjustment is needed to get a realistic estimate of the actual agricultural deficit. If it is assumed that the soil profile holds 3 inches of available water within the reach of grass roots at the beginning of the summer, then the average summer agricultural rainfall deficit at East Malling becomes 2 inches. This is a measure of the *average* irrigation requirement to keep crops such as grass from wilting. More water will be required to keep the crop growing well.

2.1.4 *Variability of rainfall*

Averages can be very misleading. Nevertheless, for the present argument, the average potential transpiration rate can be regarded as nearly enough constant from year to year, so that the occurrence of deficiencies or surpluses depends on the variability of the rainfall. There is an uneven geographical distribution in this country, separating a wetter north-west from a drier south-east, and much of the latter area has an average summer rainfall of less than 14 inches, with only 10 inches around the Thames estuary. From summer to summer these totals vary; once in ten years they may be only 40 per cent of average, and once in ten years they may be 160 per cent of average. Five years in ten the rainfall will be above average, five years in ten it will be below, so that, even in an area where the *average rainfall* is sufficient to keep plants from wilting, there is a probability of an irrigation need in five years out of ten.

Moreover, within a given summer, the month-to-month departures from monthly averages may be very great, so much so that any month can be the driest month of the year, or the wettest. There are often low rainfall periods in summers with adequate total rainfall when irrigation could well be helpful. Thus an estimate of frequency of irrigation need based on total summer rainfall is an underestimate. This is illustrated in Table 2. 1, which shows the months in which irrigation would have been beneficial during the last 10 years in the neighbourhood of Shrewsbury and of Macclesfield.

TABLE 2. 1
Months in which irrigation was needed—(1950-1959)

SHREWSBURY (yearly average rainfall 26 inches)						
Year	April	May	June	July	August	Sept.
1950		*	†	*		
1951			†	*		
1952		*	*	†		
1953		*			*	
1954	*				*	
1955				†	*	
1956		†	*			
1957	*	*	†			
1958	*					
1959		*	*	†	†	*

MACCLESFIELD (yearly average rainfall 35 inches)						
1950		*				
1951		*	*			
1952					*	
1953		*				
1954	*				*	
1955				†	*	
1956		*				
1957			†			
1958						
1959		†	*		†	*

Key: *Irrigation likely to be necessary for appropriate crops i.e. potential soil moisture deficit—1 inch.

†Irrigation very necessary for appropriate crops i.e. potential soil moisture deficit during that month—2½ inches.

N.B. This table does not take into account a succession of partly dry months.

2. 1. 5 Frequency of irrigation need

From the estimates of potential summer transpiration, computed from standard weather data, together with values of summer rainfall, it is possible, for any meteorological station that has a complete set of records, to calculate the frequency with which potential transpiration exceeds rainfall by more than

3 inches. The geographical distribution of this frequency is shown in Figure 1. The need for irrigation is almost certainly greater than this frequency for grass, vegetables and potatoes (Figures 2a and b), about the same for beans and fruit, and less for sugar beet and cereals. It shows that the frequency is greater than five out of ten to the south-east of a line from about Hull to Torquay, increasing to nine out of ten around the Thames estuary. Broadly, the boundary is that between mainly grassland farming to the north-west, and mainly arable farming to the south-east. The map ignores hill areas, where the frequency will be less than indicated, and in using it as a guide to the management of arable crops other than grass, factors such as completeness of cover, height of crop, depth of roots, length of growing season, and ripening time may need consideration. The estimates of need, whether as totals or as frequencies, are meteorological estimates of the inadequacy of summer rainfall to meet full transpiration demands; though they can give no information about crop requirements, they show clearly that the part of England where irrigation is most needed is the south-east. Even north and west of the Hull-Torquay line, conditions may be too dry for certain crops in some years; and the area where irrigation may be usefully applied to certain of the more valuable crops may well extend into most parts of England and Wales having an annual rainfall of less than 35 inches, and parts of Scotland having an annual rainfall of less than 30 inches, especially those with dry periods in the summer months. In geographical terms this is much of lowland Britain.

2.2 BASIC EFFECTS

Adding irrigation water to the soil has much the same effect as rainfall: it wets the top layer of soil to field capacity, and reduces the soil moisture tension within that layer to its value at field capacity. Depending on the susceptibility of the crop to high moisture tensions, the possibility of checks to growth is reduced, the availability of nutrients may be increased, and, in general, there is a greater leaf growth from which roots, shoots and fruits benefit. Whether irrigation is worthwhile depends primarily on the balance between the value of the increased yield and the cost of the operation, but secondary effects may be important too. The irrigated crop may be ready for market at an earlier date than the non-irrigated, though there is a tendency for irrigation to extend the period of vegetative development. As an aid to soil management it may make seed-bed preparation and the lifting of root crops easier; though some obvious reservations must be made about this kind of use on heavy clay soils.

2.2.1 *Rates and amounts*

Rates of irrigation far exceed normal rates of rainfall because any overhead irrigation system waters only part of its working area at a time, and the instantaneous peak watering rates may thus reach several inches per hour. Care is therefore needed to avoid possible damage to plants and to surface soil structure, the latter risk being greatly reduced when there is a complete crop cover to protect the soil. The effect on surface structure depends partly on the size of the drops and partly on the rate of wetting; one careless watering may result in slower uptake of subsequent rain or of later irrigation, and also reduce soil aeration.

The amount of water added should not be greater than the current soil moisture deficit, otherwise there will be wastage by drainage, and possible



FIG. 1. Frequency of irrigation need. (Years in ten).



FIG. 2A. Frequency of irrigation need for maincrop potatoes during July and August. (Years in ten).

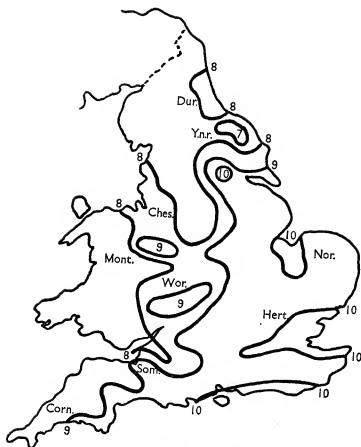


FIG. 2a. Frequency of irrigation needed for new potatoes during May and June. (Years in ten).

loss of nutrients by leaching; and it may be prudent to leave some space for the unexpected shower of rain. This may involve frequent small irrigations on shallow soils, whatever the state of the crop or its type, and on all soils carrying shallow-rooted crops. Shallow rooting, however, may be induced by over-irrigating poorly drained soils, or through failure to wet dry subsoils because of inadequate irrigation. For deep-rooted crops in general, the irrigations should be at longer intervals in greater single applications.

2.2.2 *Need for drainage*

On soil that is naturally well drained, excessive irrigation is wasteful but not always harmful; but on soil that is not well drained, excessive irrigation can lead to a rise in the water table, water-logging and restriction or killing of roots. Salinity, which is a problem in arid climates, is not likely to give trouble here, except where the source of water is brackish. There is little risk of excessive water being applied provided that proper methods of calculation and application are followed. But irrigated fields, no less than any others, should be efficiently drained, either naturally or artificially.

2.3 GUIDES TO IRRIGATION NEED

The technical problem in irrigation is to keep the inevitable changes in soil water content between a fixed upper limit (field capacity) and a variable lower limit whose value differs from crop to crop. The value of recent research is that it has improved on centuries-old empiricism in showing that, for the most efficient use of water, it is highly desirable to know the soil water conditions within the root range of the crop, i.e. to know the soil moisture stress encountered by the plant's roots. Surface appearance may mean little. A shower may wet the top inch or so of a dry soil profile and leave the remainder as dry as before: a "drying wind" may produce its peck of surface dust, but leave the bulk of the profile unaffected. Plant symptoms come too late: the wilting leaves or shrinking fruit indicate that the damage has been done. A rough estimate can be made from auger samplings throughout the rooting depth. With experience, the "feel" of the soil between thumb and forefinger can give an idea of soil dryness, and this experience can be aided by maintaining a standard set of samples at known water contents for comparison. More refined methods fall into two main groups, depending on whether the basic idea is concerned with *quantity* (i.e. soil moisture deficit) or with *tension*.

2.3.1 *Water-balance sheet*

The full method of preparing a water balance sheet, as used in a research experiment, is to collect the necessary weather data on the site and work out a weekly estimate of potential transpiration. With the rainfall, and the irrigation, if any, measured, a weekly balance sheet giving the soil moisture deficit can be kept. When this reaches some pre-determined value then irrigation is required.

On a farm only a rain gauge is needed, together with some method of measuring irrigation water applied. The estimate of potential transpiration can be obtained for any area as an average monthly value⁽²⁻³⁾ and, split up into equal seven-day equivalents, it can be used to work out the balance sheet. At the end of every summer month the National Agricultural Advisory Service issues a corrected value of potential transpiration, based on the actual weather of

that month, and if needed, adjustments can then be made to the balance sheet. The necessary changes are rarely more than trifling compared with the uncertainty in measuring the amount of irrigation water applied.

2.3.2 *Tension measurements (direct and indirect)*

In contrast with the water balance sheet, which gives an average estimate for a large area, and a total over the whole soil profile for the conditions stated in section 2.1.4 (page 8) a tension-measuring device buried in the soil only gives a measure of conditions immediately around it, but can do so continuously and with some precision. Experience indicates that a single unit, in the middle of the main layer of root development, can be adequate as a guide to when general profile desiccation has reached the stage at which irrigation is needed.

Where the soil is to be kept fairly wet all the time, a *soil moisture tensiometer* (2-2, 2-3, 2-4) can be used. It has a range from zero in a saturated soil to about the equivalent of $\frac{1}{2}$ atmosphere suction, i.e. it will not cover the full range to wilting (about 15 atmospheres suction). Since irrigation becomes desirable at between $\frac{1}{4}$ and $\frac{3}{4}$ atmosphere suction, skilled use of this instrument, which gives a direct measurement of moisture tension, can be a very helpful guide to water need. The soil moisture tensiometer can be particularly useful under conditions where the water balance sheet method may be unsuitable, e.g. for crops not providing full ground cover, or where an estimate over the whole profile may not be sufficiently precise.

When considerable drying of the soil is possible, either by design or accidental delay in irrigating, an *electrical resistance block*⁽²⁻⁴⁾ may be used to give an indirect measure of moisture tension. The water content of the material of the block (gypsum and nylon are most popular) comes into equilibrium with the tension in the surrounding soil, and the changes in water content produce a change in electrical resistance, which can be measured with a suitable meter. The resistance block can be used in the same way as the tensiometer to indicate that irrigation is needed when a pre-determined value of resistance has been reached. Though blocks work over a wide range of soil water content, they are not as reliable as tensiometers, and their performance depends on soil temperature and may be affected by the salt content of the soil.

2.3.3 *When to irrigate*

Each crop may have its special water needs at various stages of its growth (see Section 6); but, as indicated above, it is clear that, during the growing period, irrigation is essential before the permanent wilting point is reached and, at the other extreme, irrigation is unnecessary and wasteful at, or very near, field capacity.

Within these limits, evidence is accumulating that, for best growth, it is desirable to irrigate when the soil moisture tension in the main root zone has reached $\frac{1}{4}$ to $\frac{3}{4}$ atmosphere (i.e. 25 to 50 cm Hg). On many soils this is found to be near the point where about 50 per cent of the available water in the root zone has been used. Thus crops whose roots can tap a reserve of 2 inches of water, can usefully be irrigated when the soil moisture deficit reaches 1 inch; and one whose roots tap 6 inches of water, when the soil moisture deficit reaches 3 inches. For some glasshouse crops (e.g. tomatoes) and certain vegetables rather wetter irrigation regimes have been found economic, i.e. watering before the deficit reaches half the available reserve.

In practice, if water and labour are available, it is sensible to irrigate sooner, rather than later, for if the soil water reservoir is kept "topped-up" when convenient, it frees irrigation equipment for use elsewhere at other times. In addition, the soil is less likely to become cracked and the water less likely to run away through the cracks.

REFERENCES

- 2.1 PEARL *et al* 1954. The calculation of irrigation need. *Technical Bulletin No. 4 Ministry of Agriculture*. H.M.S.O., London, pp. 37.
- 2.2 ROGERS, W. S. 1936. The relation of soil moisture to plant growth, illustrated by moisture meter experiments with strawberries. *Ann. Rep. East Malling Research Station* 1935, 111-120.
- 2.3 GOODE, J. E. and HYRYCZ, K. J., 1960. The soil moisture tensiometer: its practical value for field use in fruit crops and its construction. *Ann. Report, East Malling Research Station*, 1959, p. 78-84.
- 2.4 EASTWELL, B. A., 1953. *In situ* methods of measuring soil moisture content—a critical résumé. *Tech. Rep. Brit. Electric Res. Assc. W/T27*, pp. 19.

SECTION 3

WATER SUPPLIES

3.1 SOURCES OF WATER

Rain is the principal source of water in this country. Rainfall may percolate, run off or evaporate, depending upon the topography, geology, nature of soil and the climatic and vegetational conditions prevailing at the time. Water which percolates may reappear as surface water and *vice versa*, and this can happen several times during its progress to the sea. In England and Wales, the greatest surface run-off occurs in the west, in the higher and more rocky areas of Wales, and in the north and north-west. In south-east England, where rainfall is less, the land generally is less hilly, transpiration and evaporation are greater and there is less run-off. Permeable strata underlie a large part of this area and more water percolates underground. Consequently some parts have underground water resources which compensate for the lower run-off.

On average, the recharge of aquifers and the run-off from the land is much greater in winter than in summer because, although winter rainfall is slightly higher, evaporation and transpiration are much lower. The average annual run-off from some of the rivers of south-east England, for example, is roughly equivalent to 5 inches of water over the whole area but about 4 inches of this occurs in the winter. In some years the summer run-off is only a fraction of an inch and the flows of some rivers are extremely low. Many smaller water courses dry up unless fed by springs. Field drainage systems generally cease to run in the spring.

Supplies for all purposes have to be derived either from surface flows or by the abstraction of ground water, with storage if the required rate of supply exceeds the available flow or abstraction rate. Abstraction of ground water is controlled by Act of Parliament and abstraction of surface flows may be in the near future. Public and industrial supplies have priority, and they have the great engineering asset of fairly constant demand from day to day, and from year to year. The irrigation requirement is always a summer requirement, the peak load, which depends on acreages as well as weather, is likely to be from mid-June to the end of July. These peak requirements occur when surface flows are at or near their minimum and when underground stores are decreasing, and almost inevitably coincide with an increased demand from other users.

3.2 PRESENT METHODS OF SUPPLY

There are three main methods of obtaining water for irrigation at the present time; the most popular, because it is the cheapest, is direct abstraction from streams and rivers, and up to now it is mainly this method that has been used. There is obviously a limit, however, to the amount of water which can be taken for irrigation purposes from rivers in dry weather in relation to other demands, including public, industrial and normal agricultural requirements, especially since sufficient flow has to be maintained for the support of fish life, navigation,

sewage effluent dilution and general amenity. On some rivers, in the opinion of the River Boards, confirmed by the recent C.A.W.C. report⁽⁹⁻¹⁾, this limit has already been reached.

Ground water from wells and boreholes may sometimes be used, depending on local geology and the needs of other users. A number of farmers already use ground water, but in some areas, particularly in south-east England, ground water is the main source of public water supply. Each new abstraction lowers the ground water level locally and may affect the supply to existing boreholes. Ground water is now conserved in most of the best water-bearing areas of the country under the Water Act (1945) and a licence is needed to draw additional quantities of water by sinking or enlarging a well or borehole in these areas. This, however, does not necessarily mean that ground water may not be available for irrigation purposes in some areas.

Water from public mains, produced to much higher quality than is required for irrigation, is only rarely available in sufficient quantity for farm irrigation, and is usually considered too expensive for any but high value crops. It is much used for market garden crops, where acreages and requirements are much less, and returns are higher. Because of limitations imposed by the public mains, supplies for farm irrigation, if permitted, have usually to be taken into storage at night time, and the cost of storage further increases the capital outlay.*

On most farms the flow available from any kind of source is inadequate for irrigation without storage. An increasing number of farmers have faced up to the storage problem and now have reservoirs of various kinds. Since 1956 the Ministry of Agriculture, Fisheries and Food has received applications for grant-aid towards the cost of constructing about 250 individual storage reservoirs for the irrigation of farm and horticultural crops; the largest of these has a capacity of 34 million gallons and 15 others are over 5 million gallons, 73 are between one-half and 5 million gallons, and 34 between 50 000 and 100 000 gallons capacity. The larger reservoirs were created by damming natural valleys, or by excavating in a suitable site, or by a combination of excavation and embanking. Some of the smaller reservoirs, up to about 100 000 gallons capacity, used more expensive types of construction, such as brick, concrete or steel tanks, particularly where water had to be purchased.

There are two main categories of reservoirs for storing river or stream water—those which are in line with the watercourses (impounding reservoirs), and those which are sited away from the main stream and supplied via a branch channel or pipeline (offstream reservoirs). Impounding reservoirs are formed by a dam, and have to receive the whole flow from the catchment, including flood discharges. Overflow arrangements must therefore be of sufficient size and strength to cope with the maximum discharge. For other than very low dams of about 6 feet in height, earth is likely to be the only economical material, and this can sometimes be obtained from the valley floor upstream of the dam, so creating additional storage.

Offstream reservoirs have the advantage that the flow into them can be controlled, whilst the existing natural stream carries the remainder of the flow. They can be constructed by embanking, by excavation or by a combination of

*Most rural mains are 3 or 4 inches in diameter. The maximum discharging capacity of a 4-inch pipe is about 4 000 gallons per hour; this can be compared with 8 000 gallons per hour, which is what is required for a farm of 40 acres, when the application rate is 1 inch in 10 days and there is irrigation for 12 hours each day.

both methods. Filling has to be by gravity or pumping according to the relative levels of the stream and the top water level in the reservoir. Offstream reservoirs are less dependent on ground contours than impounding reservoirs, and it is usually therefore less difficult to find sites for them.

3.3 METHODS OF INCREASING SUPPLIES

Fundamentally there are only four methods of increasing water supplies for any purpose. The first method, and the most practicable one for irrigation at the present time, is increased conservation, principally of winter run-off, by storage above or below ground. A considerable amount of conservation already takes place naturally in ponds and lakes, in the soil, and in underground strata. The prospects of increasing conservation above and below ground are considered in the following sections.

The second method is the transfer of water from high rainfall areas by pipeline or canals, but many of the best gathering grounds are already being used or likely to be utilized. It appears unlikely that such extensive works would be undertaken for irrigation purposes alone under present conditions. The third method, demineralization of sea water, is not at present a practical proposition for farm crop irrigation, because of high cost.

The fourth method is the increase of rainfall by artificial methods, but whilst there may be some prospect of increase in regions in the neighbourhood of high ground facing the sea, such as Wales, it is understood that no worthwhile contribution could be expected from this method over other parts of the country even if it were politically practicable.

3.3.1 *Surface water storage*

Storage in small reservoirs serving individual or, possibly, small groups of farms is the most practical method at present, and likely to remain so in future. These have the merit of flexibility, water is available where it is needed, poor land can often be used as a site without affecting existing development, and the financial outlay for each reservoir can be related to the benefits expected from a reasonably defined area of land. The individual farmer has the whole project under his control, and it is up to him to make it pay in the same way as any other farm enterprise. For any appreciable development of this nature oversight of the planning, design, construction* and operation is necessary to ensure safety and economy.

Ready-made storage reservoirs, drawing upon varying proportions of surface and ground water, are available in some localities in the form of gravel, clay or marl pits. Some of these are of considerable size, but although they may be full of water this may have accumulated over a long period, and the quantity of water which can be abstracted annually may be much less than the capacity, especially with clay and marl pits. Some gravel pits on the other hand may have a considerable potential inflow of ground water.

Large reservoirs serving considerable areas of land may need to be considered in the future, but there will be difficult problems to overcome. Their high cost demands much closer consideration of the economic factors and the likely demand for any water provided. In south-east England reservoir sites commanding adequate catchments are difficult to find, as is evidenced by the problems

*At present only reservoirs of greater than 5 million gallons capacity required the services of a qualified Civil Engineer—Reservoirs (Safety Provision) Act, 1930.

which have faced water authorities in providing storage for public supply. A further problem is the distribution of the water to a large area.

3.3.2 *Ground water storage*

In the long term, more conservation may be achieved by increasing infiltration to underlying permeable strata, so making use of natural storage capacity which in some areas is considerable. This form of conservation is receiving increasing attention overseas especially in the U.S.A., Sweden, the Netherlands, Western Germany and, to a small extent, in this country, but its potentialities have not yet been evaluated for conditions here. Artificial recharge of this kind is now providing one-third of the water supply in Western Germany. In England some experimental recharge through boreholes has been carried out in the Lea Valley by the Metropolitan Water Board during the years since 1954. For these experiments filtered river water, which was also chlorinated, was fed through boreholes into the Thanet Sand and the Upper Chalk of the Lower Lea Valley. In these experiments the quantity of water recovered was 38 per cent, and more could have been recovered if the works had been specially designed and sited for maximum recovery. The feasibility of this approach is dependent on geology, and in any area considered permeable strata with unreplenished storage capacity must be present and accessible. Various methods of recharge are possible of which the most promising for use in this country is the diversion of surplus flow into gravel deposits, wells or boreholes. Aquifers used for public supplies would have to be safeguarded against contamination especially when water is introduced directly into water-bearing strata.

3.3.3 *Planning and co-ordination*

Such developments can only be properly planned as part of a comprehensive river control concept. Irrigation requirements would need to be considered in relation to other water supply requirements, navigation, fisheries, dilution of effluents and in certain circumstances, flood alleviation. Furthermore the day-to-day operation of storage works would need to be properly co-ordinated and supervised to ensure efficient use of the resources available.

REFERENCE

- 3.1 Central Advisory Water Committee (1960). *Sub-committee on the Growing Demand for Water, Second Report* (S.O. 5-9999) H.M.S.O. London.

SECTION 4

METHODS

4.1 METHODS

Of the three kinds of irrigation practised in this country, sub-surface, surface and overhead irrigation, all but a negligible proportion is overhead irrigation, and this is the method that is most likely to be used in the future. Technical advances in the design of this equipment have enabled it to be handled easily and have encouraged its use.

4.2 SUB-SURFACE IRRIGATION

In sub-surface irrigation, water is fed to plants at their roots by raising the water table, but this method is only feasible in certain areas, principally the Fenlands. Much of this area is below sea level so that drainage ditches have to be pumped out in the winter to prevent flooding. During the summer the level of the water table can be controlled by refraining from pumping or by reversing the winter flow.

4.3 SURFACE IRRIGATION

There are two main methods of surface irrigation. In the first, *furrow* irrigation, furrows are drawn parallel and close to one another: water is run into the furrows and crops are grown on the ridge. In the second, *flood* irrigation, the land has to slope away from the water source to enable the water to spread over the whole area. Water meadows are a commonly-occurring example.

4.3.1 *Limitations of surface methods*

Land suitable for surface methods is not common in this country. Land, with a gentle and regular slope is required, but owing to the general absence of deep topsoil, it is rarely possible to grade the land artificially even if the expense of doing this were not prohibitive. Many soil types are unsuitable: water can percolate through highly pervious soils precluding the efficient use of small quantities of water, and with any soil type the use of water is inefficient and probably in excess of the soil moisture deficit. Soil erosion may also be serious. In furrow irrigation, the water channels reduce the area available for planting certain crops, and weeds may grow in them.

4.4 OVERHEAD IRRIGATION

4.4.1 *Equipment*

Water pumped at pressure and conveyed through pipes is sprinkled over the land from rows of nozzles in pipelines ("spraylines") or from nozzles in rotary heads ("sprinklers" or "rainguns" depending upon their size of nozzle). Generally the raingun works at a higher pressure, delivers more water and covers more land than the sprinkler (Table 4.1) but with both the water issues as a jet which is then broken up mechanically. Some forms of sprayline can be oscillated automatically so that the land on each side of them is watered. This reduces the application rate which is attained if the pipe is stationary for

a period and moved by hand at intervals, and enables a larger area to be covered at one setting.

With sprinklers and rainguns some additional irregularity of distribution results from the fact that circular areas are covered, but this can be largely compensated by suitable overlap. The uses to which the various types of overhead equipment may be put, together with their more important characteristics are given in Table 4. 1.

TABLE 4. 1
Characteristics of overhead irrigation

Description	Water Pressure lb/sq in.	Water Through-put gal/min	Area covered per setting	Applica- tion rate in/h	Appropriate use
<i>Spraylines</i> Oscillated pipes 1 in.-2 in. diameter. Nozzles along lines about 2 ft apart	Low to Medium 20-60	Between 1/20 and 1/4 per nozzle	Varies with nozzle through- put which can limit the length to about 300 ft Width about 45 ft	$\frac{1}{2}$ -1	Intensive horticulture, orchards, glasshouses
<i>Sprinklers</i> One or more rotating nozzles less than $\frac{1}{2}$ in. diameter	Medium 30-60	Up to 10 per sprinkler	30 to 90 ft diameter. Used in gangs, 20 usually cover one acre	$\frac{1}{2}$ -1	All crops
<i>Rainguns</i> One or more rotating nozzles greater than $\frac{1}{2}$ in. diameter	High 60-120	Between 50 and 400 per raingun	120 to 360 ft diameter cover $\frac{1}{2}$ -2 acres	$\frac{1}{2}$ -1 $\frac{1}{2}$	Crops which give good protection to the soil such as grass and sugar beet

4. 4. 2 Types of system

Several types of system are in use; the choice between them depends on the available capital, crop and soil type, topography and availability of water.

- (a) *Permanent.* In permanent systems, the pump and all pipework including the sprinkler equipment are fixed. Such a system is expensive and is warranted only in special cases outdoors but is common in glasshouses. It is cheapest to run as labour costs are small. Permanent mains may be laid to take water through land that is not being irrigated.

- (b) *Semi-permanent.* In semi-permanent systems, the main distribution pipes are fixed, and are usually buried. The overhead sprinkler equipment is fed from the main using stand pipes placed at convenient points.
- (c) *Portable.* With portable systems, as well as sprinkler equipment, the distribution mains and the pump are moveable. The pump is most commonly driven by a tractor power-take-off shaft, and draws water from such sources as rivers, lakes and reservoirs. The pipes have "quick couplings" between the sections so that they can be taken to pieces and carried about the farm.

In some systems the labour handling small parts of equipment is reduced. For example, "tow-a-line" systems and "roll-a-line" systems enable complete laterals to be moved, often mechanically, by one man in a very short time. The initial cost is considerable, the land must be fairly level and the crops grown must be able to withstand the passage of equipment over them.

4.4.3 *Advantages of overhead irrigation*

Overhead irrigation can be used on hilly or even mountainous terrain. It is flexible; the application rate, operating pressure and corresponding nozzle size can be selected to suit the soil type and its particular infiltration rate; the pipelines can be placed between the crop rows and no land need therefore be taken out of production.

Very little of the water supplied need be wasted, evaporation loss from the spray being usually negligible: overhead irrigation requires about one-third the quantity of water, for the same crop treatment, as surface methods.

Additional uses of overhead irrigation equipment for protecting plants from frost, for distributing fertilizers or for distributing organic manure, are described in Section 6.6.

4.4.4 *Limitations of overhead irrigation*

Care needs to be taken in the use of all irrigation equipment. Even if breakup of the jet is complete, the water reaches the ground as water drops of various sizes. Large drops, with high terminal velocity, have considerable kinetic energy and can damage the soil surface by breaking down the soil crumbs and choking the interstices. This process, called "capping", seals the surface against the passage of gases or water. In particular, equipment which produces large water drops—in most cases rainguns with large jets intended to cover large areas—should not be used on soil which is not protected by a covering crop.

Winds can seriously interfere with the efficiency of distribution, particularly from rainguns, although special sprinklers can be used if the prevailing winds are high.

SECTION 5

COSTS*

5.1 OPERATING COSTS

Little information on the average costs of irrigation in England is available. The following discussion is based largely on the results of two surveys (8-1, 5-6) supplemented by information from manufacturers and other sources, including Ministry of Agriculture data from grant-aided schemes. The survey made by the Farm Economics Branch, Cambridge University, examined the costs on twenty-seven farms in the Eastern Counties in 1955-57. Generally, rotary sprinklers were used, and most of the equipment was portable; on nearly all the farms "free" water from rivers was available. The second survey was made by the Ministry of Agriculture's Land Drainage and Water Supply Division for the Agricultural Improvement Council. It covered fifteen farms, of which twelve provided adequate records of costs, distributed widely over the south east of England, and special records were kept by the farmers. Here again, most farms used rotary sprinklers and portable equipment; twelve out of fifteen obtained their water from rivers, streams or dykes but three had had to provide source works. The Cambridge figure is fairly typical of the farm scale irrigator who predominates at the present time, using mainly portable equipment, with free water from rivers. Average costs will undoubtedly increase in the future as more and more farmers have to incur expenditure on source works, or are charged for abstractions from rivers.

5.1.1 *Average costs*

Total operating costs consist of the annual fixed costs—mainly depreciation and interest on capital—and running or variable costs—mainly labour and pumping. The average costs per acre-inch applied in the two surveys, with costs adjusted to 1961 levels, are given in Table 5.1.

5.1.2. *Range in costs*

For each item of costs there was a wide range. Both the extremes and the main range for the principal items are given in table 5.2 for the two surveys separately. Costs were fairly evenly distributed over the main range.

5.1.3 *Fixed costs*

The constituents of capital cost and the reason for variations between irrigation plants, even of similar size, are described in Section 5.2. The annual charge that should be included in the costs to cover any given item of capital expenditure depends on the rate of interest, and on the estimated useful life of the works or equipment. In assessing the latter, obsolescence and possible cessation of need must be taken into account as well as deterioration. The individual farmer has also to consider his total available capital resources and competing demands upon them. The farmer's difficulty in obtaining the necessary capital is, however, reduced since permanent irrigation works (including fixed pumps and permanent mains) qualify for a 40 per cent grant from the Ministry

* This section refers primarily to farm-scale irrigation. Market garden costs are normally higher.

TABLE 5.1
Average costs per acre-inch* (shillings)

Item	Cambridge Survey (27 farms)	A.I.C. Survey (12 farms)
Depreciation and Interest	25	43
Labour	10	10
Pumping†	10	7
Other costs	2	8
Total operating costs‡ per acre-inch	47	68

*After deduction of grant.

†Including tractor costs where tractor-operated pumps were used, i.e. on all but two of the Cambridge Survey farms, but on only half of the A.I.C. Survey farms.

‡The total cost in the A.I.C. Survey was higher than that in the Cambridge Survey for three main reasons: first, the average capital cost of the A.I.C. survey schemes was higher, since more farms had incurred expenditure on source works and permanent equipment; secondly, two of the survey farms used their equipment very little, giving an abnormally high depreciation and interest cost per acre-inch; thirdly, the A.I.C. estimate of repairs (included in "Other costs") was higher.

TABLE 5.2
Range in costs per acre-inch (shillings)
After grant has been deducted

Item of cost	Range	Cambridge Survey	A.I.C. Survey
Depreciation and Interest	Extremes Main range	6 to 50 10 to 46	8 to 190 8 to 44
Labour	Extremes Main range	4 to 25 4 to 16	3 to 23 3 to 16
Pumping	Extremes Main range	4 to 26 4 to 16	3 to 16 3 to 9
Total Running Costs	Extremes Main range	12 to 45 12 to 29	6 to 30 6 to 22
Total Costs	Extremes Main range	18 to 83 23 to 65	19 to 250 28 to 84

of Agriculture (25 per cent if water is supplied from a public main), provided the scheme has been approved by the Ministry. This also increases the long-term financial advantage to the farmer of an irrigation scheme with permanent works. Thus, with an interest rate of 6 per cent, the interest and amortisation required for a loan of £1000 which is to be liquidated in 20 years, is £87 per annum, whereas with a 40 per cent grant and repayment of the remainder in 10 years the amount is £82 per annum.

In what follows, a useful life of twenty years is assumed for source works and fixed equipment qualifying for a Ministry grant, and ten years for portable equipment, with an interest rate of 6 per cent on capital. This gives an annual charge of £87 per £1000 for permanent works and £136 per £1000 for other equipment. The full cost, without taking the Ministry grant into account, has been shown in all cases.

The annual fixed cost per acre-inch depends on the capital cost of the equipment, the number of acres irrigated and the average quantity of water applied per acre (see Table 5.3).

TABLE 5.3
Variations in fixed costs per acre-inch

Capital cost per acre (£)	Annual fixed cost per acre* (shillings)	Fixed cost per acre-inch (shillings)			
		Average number of inches applied per acre per annum			
		1	2	3	4
20	54	54	27	18	14
40	89	89	44	30	22
75	150	150	75	50	37

*Assuming £20 capital cost is portable equipment and the rest permanent works.

Within the range shown in Table 5.3, therefore, fixed costs per acre-inch vary from 14s. (a capital cost of £20 per acre and an average annual use of 4 inches) to 150s. (£75 per acre capital cost and an annual use of 1 inch per year). It is thus important not to under-utilise the equipment, particularly where capital costs are high.

5.1.4 Running costs

Running costs must be added to the fixed costs to give total operating costs. Broadly speaking, total running costs vary from 10s. to 30s. per acre-inch, and consist of the following items.

(a) *Labour*. Average labour costs in the Cambridge survey were 10s. 3d. per acre-inch, and in the A.I.C. Survey, 10s. 0d., assuming an average wage rate of 4s. 6d. per hour. There was a wide range, from 4s. 3d. to 24s. 9d. in the former survey and 3s. 3d. to 23s. 3d. in the latter. Only on a few farms, however, did labour costs exceed 16s. 0d.

When irrigating, labour is needed at more or less regular intervals throughout the day to move the rainguns, sprinkler lines or spraylines, and attend to the pump. In addition, where portable mains are used, these have to be moved

periodically. Moving a long length of main from one part of the farm to another may take a gang of three or four men half a day. Moving the sprinkler line takes about two-thirds of the labour time on average but it is more easily fitted in with other work on the farm than the irregular large moves.

Employing one or more men full time on irrigation is often the most efficient method with large schemes, but it can be expensive on small schemes because the man or men are under-employed. There are other important points such as the lower labour requirements of permanent equipment; electrically driven pumps require less attention than those driven by liquid fuel engines (particularly when these are old tractors); equipment is moved more easily and quickly on grass than arable crops, particularly late in the season.

(b) *Transport.* Tractors and trailers or lorries are required for transporting portable equipment round the farm, particularly where the irrigated area is scattered. The average cost of this was approximately 1s. 0d. per acre-inch on both surveys.

(c) *Pumping.* Fuel costs for pumping depend on the size, type and efficiency of the pump, and the severity of the work it has to do. In particular, the quantity of water pumped, the length and diameter of the mains, and the pressure required at the nozzles affect fuel costs. The average cost in the two surveys was 4s. 0d. per acre-inch, with a range from less than 2s. 0d. to nearly 7s. 6d. Other tractor costs besides fuel, i.e. depreciation, servicing and repairs, total approximately 2s. 6d. per hour and amount on average to 6s. 0d. per acre-inch. This makes total pumping costs 10s. 0d. per acre-inch for tractor-driven pumps.

(d) *Repairs and maintenance.* Repairs and maintenance costs should be low, consisting mainly of periodic overhauls of the pump, occasional repairs to pipes and small part replacements such as the rubber rings in the pipe connections. Repairs and maintenance costs in the Cambridge survey were just over 1s. 0d. per acre-inch including bringing in the equipment at the end of the season and storing it away.

5.2 CAPITAL COSTS

The total capital cost of irrigation is the sum of the expenditure on the following items:

- (1) Source works.
- (2) Distribution equipment:
 - (a) pumping equipment,
 - (b) pipeline,
 - (c) sprinkler line, sprayline or raingun.

5.2.1 Source works

Up to the present, most irrigation schemes have been able to obtain an adequate supply of water from rivers, streams, springs or lakes without charge and with no capital expenditure on source works. As the use of irrigation spreads, however, more and more irrigators will have to invest capital to provide the necessary water supply. Expenditure on source works varies considerably; and can double or treble the initial cost. One or more of the following may be needed:

River intake works, spring collection works, well or borehole, reservoir, contribution towards the cost of a public supply system.

Boreholes and reservoirs are the most important at present.

(a) *Boreholes.* Borehole costs depend on many factors; such as depth, diameter, the nature of the strata, the extent of lining required, the need for screens and the duration of testing. Furthermore, contractors' charges vary widely between districts. Depths vary most commonly between 50 feet and 300 feet. Most boreholes cost between £1 and £8 per foot, the most likely range being between £2 and £4 per foot. The cost can vary, therefore, from £200 to £2000, although it is unlikely to be less than £500. For 50 acres irrigated, this is a cost of £10 to £40 per acre, equivalent to between 17s. 0d. to 70s. 0d. per acre per annum. In addition, boreholes normally require more expensive pumps than surface sources.

(b) *Reservoirs.* Except in very favourable conditions, reservoirs are more expensive than boreholes; their cost depends primarily on their nature and size. Concrete, brick or steel tanks may be used for units with a small capacity, i.e. between about 10 000 and 100 000 gallons, and where, because of small or expensive water supplies, it is important to prevent losses. Costs vary from about £40 to £50 per 1000 gallons storage.

Large capacity reservoirs may be of the impounding type with an earth dam, or may be of excavated earth. Earth reservoirs vary widely in cost, even for a given water requirement, according to the following factors:

- (1) The water: earth ratio, i.e. the storage volume made available by the movement of a given volume of earth.
- (2) The cost per cubic yard of excavation. This varies considerably according to the standards of design and workmanship. Most earthworks cost between 2s. and 4s. per cubic yard but the cost can be as high as £1 per cubic yard.
- (3) The extent of overflow works and inlet and outlet arrangements. These are normally more expensive for impounding reservoirs than for excavated, off-stream reservoirs, but even for the latter the cost can equal the cost of excavation.
- (4) The cost of design and supervision of construction.
- (5) The value of the land flooded. One million gallons (44 acre-inches) will cover half an acre 7 feet deep. Enough water to put 4 inches on 100 acres will cover nearly five acres at this depth.

The cost of excavation with a water: earth ratio of 2:1, combined with an earthworks cost of 2s. 6d. per cubic yard, amounts to £370 per million gallons. The total cost is commonly within the range of £500 to £1000 per million gallons capacity. A cost of £750 per million gallons capacity is equivalent to 1s. 3d. per 1000 gallons or 29s. per acre-inch,* when the whole of the capacity is used once each year. The cost per million gallons actually used may be more or less than this cost. It will be more when there is no replenishment during the irrigation period. How much more will depend on:

- (1) The extent of losses from evaporation and leakage; the former is not usually serious in this country but loss from the latter can be considerable.

*These costs may be compared with the cost of mains water—where this can be purchased—of between 2s. 0d. and 4s. 6d. per 1000 gallons.

(2) The extent to which the reservoir is designed to satisfy peak requirements: if the reservoir can provide all the water needed even in the driest years then clearly there will be under-utilization in most years.

On the other hand, the cost per million gallons used may be considerably reduced if the reservoir is periodically replenished during the irrigation period.

5.2.2 Distribution equipment

(a) *Pumping equipment.* The cost of pumping units depends on the output required, total head, method of driving and specification. Permanent installations require a pumphouse. Up till now, for farm-scale irrigation using water from rivers or streams, tractor-driven portable pumps have been most popular. Most of those capable of medium or large-scale irrigation (an inch of water applied in 3—4 hours to 1—3 acres at a setting) cost between £200 to £220, including all necessary accessories such as the suction and delivery hoses. There are, however, cheaper pumps available.

Where combined pump and power units are either preferred or essential, costs are rather higher. Diesel engine driven pump units cost between £350 and £800 according to the capacity and pressure required; electrically-driven pump units are cheaper, except where provision of the necessary power supply is expensive.

Pumps for wells and boreholes are more elaborate, and, together with installation, are likely to cost at least £500. In fact, high capacity submersible pumps may cost £1500 or even more, but the provision at the head of a borehole of a storage tank and a separate pump for distribution may reduce costs where such high capacity is required.

(b) *Pipeline.* (1) *Portable mains.* Most portable mains in this country are made of aluminium alloy. Average prices per yard for pipes in 30 feet lengths, including couplings and with valves at every 60 feet, are as follows:

3 inch diameter—20s. 0d. 4 inch diameter—25s. 0d.

5 inch diameter—30s. 0d. 6 inch diameter—45s. 0d.

Prices of individual firms vary within a few shillings of these figures.

To keep friction loss within reasonable bounds pipe diameter has to be increased as the distance of irrigated fields from the source increases (see Table 5.4).

If delivery rates greater than 250 gallons per minute are required, or the farm is hilly, the main would cost still more, assuming the same pump were used. In these circumstances, however, this cost could be reduced if a more powerful pump were used.

(2) *Permanent mains.* On average the price per yard run for permanent piping, including laying, is similar to that for portable. Cheaper materials such as asbestos cement can be used, which offsets the cost of laying, so that the cost at the larger diameters may, in fact, be less than for portable piping. Including hydrants at 100 yard intervals, average prices per yard are as follows, the range being broadly 5s. 0d. per yard either way:

3 inch diameter—20s. 0d.

4 inch diameter—25s. 0d.

5 inch diameter—30s. 0d.

6 inch diameter—35s. 0d.

Permanent mains can qualify for a 40 per cent grant. The cost per yard run will then be only one-half to two-thirds the average price of portable pipes. Nevertheless, even with a grant, permanent mains may be more expensive than portable mains. This is because portable mains can be transported round

TABLE 5.4
Approximate cost of portable main*

Length of main— (miles)	Output			
	125 gal/min		250 gal/min	
	Pipe diameter (in.)	Cost (£)	Pipe diameter (in.)	Cost (£)
$\frac{1}{4}$	All 4	550	All 5	650
$\frac{1}{2}$	All 4	1100	All 5	1300
$\frac{3}{4}$ †	$\frac{1}{2}$ mile 4, $\frac{1}{4}$ mile 5	1750	$\frac{1}{2}$ mile 5, $\frac{1}{4}$ mile 6	2650
1†	$\frac{1}{2}$ mile 4, $\frac{1}{4}$ mile 5	2750	All 6	4000

* Assuming a tractor-driven pump and a total head of 210 feet.

† Mains of these lengths are unlikely to be entirely portable.

the farm and used to irrigate more than one piece of land. A permanent main will occasionally be cheaper, particularly on a long, narrow farm with the source at one end, and is worth considering in many other situations, since the greater convenience and lower labour costs may well be sufficient to compensate for a slightly higher total cost.

For bringing water from outside the farm across land that is not to be irrigated, the cost per mile using a 6 inch permanent main would be about £2750 without grant and £1650 with a 40 per cent grant.

(c) *Sprinkler line and raingun.* Most sprinkler couplings, stand-pipes and sprinklers are 3 inches in diameter and cost between 20s. 0d. and 22s. 6d. per yard. Lines are usually spaced about 60 feet apart. Thus 240 yards, costing between £240 and £270, will suffice to cover an acre at each setting. This length will normally have 20 to 24 sprinklers at 30 to 35 feet intervals. Sprinkler line of 4 inches diameter costs 25s. 0d. to 27s. 6d. per yard inclusive and line of 2 inches diameter 15s. 0d. to 17s. 6d. per yard. Examples of raingun costs are 0.4 acre-inches per hour, £40; 0.8, £90; 1.5, £110. Laterals of 3 inches diameter with couplings and valves, cost 18s. 0d. per yard, and of 4 inches diameter cost 22s. 6d.

The relative costs of sprinkler and raingun systems depend on many factors. With greater volumes and distances, the higher pressure required to operate rainguns may necessitate larger diameter pipes and/or a larger pump. If the pump has spare capacity, the faster application rate associated with rainguns may reduce capital costs because—with more frequent moves—a smaller amount of equipment can cover the same ground per day. However, there are certain drawbacks to faster application rates and the larger droplet size of rainguns (see Section 4).

The cost of $1\frac{1}{2}$ inch diameter aluminium alloy oscillating sprayline, with supports, is between 13s. 0d. and 18s. 0d. per yard. Steel sprayline costs a few shillings per yard less and $1\frac{1}{2}$ inch diameter sprayline a few shillings per yard more. Oscillators usually cost between £20 and £30. *

5.2.3 *Capital costs on the individual farm*

The total capital cost includes pumping unit, pipeline and portable spray equipment. Where an adequate free surface flow is not available the cost of source works—usually a borehole or reservoir—is additional.

The design of the scheme is of primary importance in determining the capital cost. The following affect the initial cost of a particular scheme, given the area to be irrigated each year and the quantity of water required.

(a) The nature of the water source, i.e. whether an adequate supply of free surface water is available or whether source works are needed. This also affects the type of pump required.

(b) The location of the source in relation to the area to be irrigated. This affects the length of main needed and possibly the size of pump.

(c) The shape of the area to be irrigated, and whether, and to what extent it is scattered over a larger area. This affects the length of main line required and perhaps the size of pump. The size and shape of fields may also affect the amount of equipment required, and the topography may affect the size of the pump needed. Where crops such as sugar beet or potatoes are to be irrigated, the fields to be watered will differ from year to year for rotational reasons; the initial cost for a given irrigated area will then generally be higher than where the same fields are irrigated each year, as with permanent grass or mixed vegetables. In the former case the area that has to be reached by the equipment may be considerably greater than the area to be irrigated in any one season.

(d) The water application rate, the number of hours per day (and night) the equipment is operated, and the frequency of irrigation need in terms of the interval between successive applications in a dry spell. Between them these factors determine the length of sprinkler line or the number of rainguns needed. The figure for "safe application rate", the hours per day that the equipment can be used, and the frequency of irrigation need in a dry spell all influence the amount of equipment required.

Not all crops need to be irrigated during the same cycle period, e.g. early potatoes need irrigating in a dry May, but not sugar beet; sugar beet needs irrigating in a dry July, after the early potatoes have been lifted (Appendix A). Only the acreage to be covered within the peak irrigation period need be taken into account when estimating the length of sprinkler line or number of rainguns required.

Examples of initial capital cost. Assuming that one acre can be irrigated at a setting, that an inch of water can be applied in $3\frac{1}{2}$ hours, including moving the sprinkler line, and that the plant can be worked 14 hours each day, a unit of 40 irrigated acres can be given an inch of water in ten days.

The lowest cost is where the whole of the irrigated area lies alongside a river, from which free water is available. Assuming it is all within some 240 yards of the river, only a short length of portable main would be needed—to save having to shift the pump at each setting. A 40 yard length of main would give

five settings from the same pump position. The total cost is approximately £13 0s. 0d. per acre, made up as follows:

Pump (tractor driven, with accessories)	= £200
Sprinkler line	= £270
Main	= £40
Miscellaneous	= £20

This cost can be reduced slightly by increasing the application rate, by working the plant all night, or by having a longer cycle. Since the same pump will often be adequate for 500 to 100 acre schemes, the capital cost can be as low as £10 per acre.

The further the irrigated area lies from the water source and the more scattered the areas to be irrigated, the higher the initial cost. In general, the initial cost of irrigation schemes, excluding the cost of source works, averages about £25 per acre irrigated within a given cycle period.

Examples of total capital costs when source works are required are given in Table 5.5. In calculating the cost the mains have been assumed to be half portable and half permanent, except for the 100 acre scheme with $\frac{1}{2}$ mile piping, where the main has been assumed to be made up of $\frac{1}{2}$ mile of permanent main, 6 inches diameter, and $\frac{1}{2}$ mile of portable main, 5 inches diameter. The pump units are assumed to cost £500 (50 acre schemes) or £600 (100 acre schemes). The figures in brackets represent the cost to the farmer if a 40 per cent grant has been obtained on all the fixed equipment.

Table 5.5
Capital costs at three levels of source work costs—£

Cost of Source Works	Size of area irrigated—acres							
	50				100			
	$\frac{1}{2}$ mile of main		$\frac{1}{2}$ mile of main		$\frac{1}{2}$ mile of main		$\frac{1}{2}$ mile of main	
	Total cost	Cost per acre	Total cost	Cost per acre	Total cost	Cost per acre	Total cost	Cost per acre
1000 (600)	2400 (1700)	48 (34)	3000 (2100)	60 (42)	3600 (2700)	36 (27)	4500 (3200)	45 (32)
2000 (1200)	3400 (2300)	68 (46)	4000 (2700)	80 (54)	4600 (3300)	46 (33)	5500 (3800)	55 (38)
4000 (2400)	5400 (3500)	108 (70)	6000 (3900)	120 (78)	6600 (4500)	66 (45)	7500 (5000)	75 (50)

REFERENCES

- 5.1 NIX, J. S. and PRICKEET, C. N. (June 1961). *Farm Crop Irrigation; The Economic Aspects Report No. 55*, Farm Economics Branch, School of Agriculture, Cambridge.
- 5.2—Agricultural Improvement Council, Land Management Committee Irrigation Investigation (unpublished information).

SECTION 6

RESPONSE OF CROPS

6.1 GENERAL

Irrigation is an attempt to make good a deficiency. In other words for a given plant variety, management and soil, the growth of the irrigated crop should differ very little from that of an unirrigated crop getting adequate rain. The need for irrigation is to some extent independent of the crop, varying with factors such as season, local weather, geographic position and soil type (Section 2). Nevertheless, different crops require different amounts of water, and at different stages in their development to ensure the best results, so that there is no one best treatment for all crops. A calendar showing the time during which the different crops are likely to require irrigation is given in Appendix A.

Most crops grown in this country have been irrigated either experimentally or under farm conditions, but information on the likely response to irrigation is still limited. Research work in recent years has concentrated on determining the timeliness of irrigation in relation to the stage of development of the crop, and the amount of water that may be extracted from the soil before a check to economic growth occurs. In general, maximum vegetative growth is obtained when the soil moisture content is maintained close to field capacity throughout the life of the crop, but the amounts of irrigation, and the stages in growth at which water should be applied to individual crops, depend on whether the economic product is leaf, root or seed.

Three aspects of response need to be distinguished. First, there is the response to irrigation when, without irrigation, the crop would be at a standstill. This is the kind of response that is obtained in drought periods, and in such years there need be no reservations in assessing the value of irrigation, whether the data have come from a controlled experiment or a farm trial. Second, there is the kind of response, or rather of responses, obtained in an experiment where there is a range of watering treatments imposed. Assuming that experience gained in this way can be exploited to improve future management, it seems legitimate to select from such a body of data the treatments that have given the greatest increase in economic yield and, with adequate statistical safeguards, to regard these best treatments as a measure of a future normal response. Third, there is the long period average response obtained by dividing the total gain over a number of years by the total irrigation applied. This gives a minimum estimate of potentialities because it includes all the over-waterings. Not all of these are blameworthy, although, as management technique improves, some of them should become so. There remains the risk of watering in ignorance of the imminence of a spell of wet weather, and it may be some decades before medium-range weather forecasts significantly reduce this risk.

All three types of response are represented in this section which sets out to specify what is known about the irrigation of field crops in Britain. There are two sources of information, and one source of inference.

(1) Controlled experiments, of which more are needed.

(2) Farming experience, which may be purely qualitative but can sometimes be supplemented by observations made by the Advisory Service using either unwatered strips, or neighbouring fields as controls.

(3) It is sometimes possible to take over results from neighbouring countries having a similar summer climate, but, unless a detailed description of the climate is available, they can only be applied tentatively. Danish, Dutch and Belgian experience has, however, provided circumstantial evidence that results from British experiments (as in (1)) are not misleading.

Where possible, yield responses have been expressed in terms of yield increase per acre inch of water applied, to simplify the reporting of the data. In fact, crop response to a given volume of irrigation water will vary according to:

1. stage of growth when the water is applied.
2. current soil moisture deficit.
3. amount of irrigation applied.
4. soil texture and structure.
5. general growing conditions.

It is therefore necessary to consider the quoted responses along with the qualifying data, e.g. for maincrop potatoes two sets of response figures are given, one relating to the amount of irrigation during the whole period of growth and one where irrigation has been restricted and applied only during tuber swelling.

At the present time, experiments are being carried out superimposing irrigation treatments on conventional methods of growing the crop, but irrigation may well demand a change in management or growing methods to produce the best returns and changes, in growing methods may also modify irrigation treatments.

Broadly, it is possible to discuss the responses of the different crops under four headings: farm crops, grass, fruit and vegetables.

6.2 FARM CROPS

6.2.1 Potatoes

Potatoes respond well to irrigation and grow best when the soil is kept close to field capacity. Preliminary work indicates that the best results are obtained if irrigation is applied when half of the available water has been used from the top twelve or eighteen inches of the soil. Under most conditions this approximates to preventing the soil moisture deficit from exceeding one inch. On this basis it is desirable to irrigate early potatoes all through the life of the crop. Recent experimental evidence has shown that with maincrop potatoes irrigation can be economically withheld until the tuber swelling stage is reached in late June or early July. This is supported by much overseas data. There are, however, varietal differences and, under prolonged drought conditions, varieties producing a low tuber number will benefit from one or two irrigations before this stage is reached.

Yield. At Woburn (Beds.)⁽⁴⁻¹⁾ *early potatoes*, lifted in July, much later than a normal farm crop, gave a mean response in 1951-53 of 1.6 tons tubers per acre-inch, representing 50 per cent increase in mean yield; the best year was 1951, with an increase in response of from 3.8 tons unirrigated to 8.1 tons irrigated when 2.2 acre-inches were applied, the worst 1953, with an increase from 11.0 tons unirrigated to 13.4 tons for 2.0 acre-inches. In the West Midlands⁽⁶⁻⁹⁾ similar increases have been obtained from crops lifted earlier, the mean response for 1956-1960 being 1.6 tons of tubers per acre-inch, representing increases in mean yield from 50 to 100 per cent. A five-year mean response of early potatoes in Denmark (1952-56) was 1.7 tons per acre-inch.

In experiments⁽⁶⁻²⁾, at Woburn and Gleadthorpe (Notts) where irrigation was applied as necessary throughout the growth period of the crop, *maincrop* potatoes gave a mean increase in response of 1 ton per acre-inch applied. For *maincrop* potatoes at Woburn⁽⁶⁻³⁾ for 1954-56, the mean response was 1.0 ton per acre-inch applied, the best year being 1955 with an increase from 11.1 unirrigated to 20.4 tons for 6.3 acre-inches applied, and the worst, 1954, with a decrease from 16.0 unirrigated to 15.1 tons for 2.2 acre-inches applied.

At Gleadthorpe⁽⁶⁻²⁾, *maincrop* potatoes were irrigated in 1955, 1957, 1958 and 1959. The mean response was near 1.0 tons per acre-inch, in spite of a completely unnecessary experimental watering in 1958. Ignoring this year, the three-year mean response was 1.2 tons per acre-inch, representing a 70 per cent increase in mean yield, with the maximum increase in 1959, from 7.5 unirrigated to 17.6 tons for 8 acre-inches applied, and the minimum in 1957, when there was a decrease from 8.8 unirrigated to 8.2 tons for 1 acre-inch applied.

Evidence⁽⁶⁻¹⁰⁾ from eight farms in 1956 and five farms in 1957 in South-East England indicated that, on average, potato yields were increased by about 2 tons per acre in both years, the amount of irrigation being just over three inches in each year.

In experiments in the West Midlands using the variety *Majestic*, for 1956-59, the mean response was 1.5 tons per acre-inch when water was applied throughout the life of the crop and the average total response 7.0 tons per acre, an increase of 60 per cent. Where water was applied from tuber swelling only, the mean response was 2.5 tons per acre-inch and the average total response 6.0 tons, a mean increase of 55 per cent. Farm trials in the same area have given similar responses, the mean response per acre-inch applied being 2.0 tons when water has been applied only from the tuber swelling stage onwards.

Quality. Properly controlled irrigation gives a greater proportion of ware-sized potatoes and can produce a much more uniform tuber sample, relatively free from secondary growth and cracking; the potatoes have better storage qualities and the specific gravity also tends to be higher^(6-4, 6-5). On land subject to Common Scab (*Streptomyces scabies*), irrigation has reduced the number of tubers affected by a substantial percentage. There are no reports indicating that the flavour of irrigated potatoes has been affected.

Tuber development. There is some evidence to show that irrigation will encourage earlier tuber set in early varieties, but since it also appears to increase the total number of tubers set, crops required for very early digging, May/June, do not benefit substantially from irrigation providing the soil is moist at planting time. For these conditions a single irrigation at "tuber swelling" will give the best returns. Where the early crop is to be lifted later than this date, larger crops are obtained by irrigating throughout the life of the crop as the percentage ware is substantially increased by earlier irrigation. At the end of the season irrigation delays the maturity of the tops and of the tubers. With very late maturing varieties irrigation should be withheld for a period before lifting, otherwise storage difficulties may arise.

Potato blight (*Phytophthora infestans*). It seems unlikely that irrigation will induce the initial appearance of blight in a crop, but when blight is present it will spread more rapidly under irrigation or in crops which have previously been irrigated. The number of tubers affected by blight, however, has been reduced by irrigation^(6-3, 6-4).

6.2.2. *Sugar beet*

Though the commercial product is sugar, the crop is valued in terms of root weight and sugar percentage; the tops may be a valuable by-product. Sugar beet is a deep-rooted crop and does not respond substantially to irrigation except on very light soils or in years where there are mid and late summer droughts. High yields are usually obtained where adequate moisture is available throughout the season but the responses obtained from irrigations early in the season are seldom economic and sometimes depress yield. Late irrigations at the end of August and in September can increase root yields but may not increase the yield of sugar. In this country the economic time for irrigation appears to be from the stage where the tops are just meeting in the row after singling until the middle to end of August. Much good commercial practice is based on a major watering (about two inches) about mid-July. Over-irrigation carried out early may lead to "fangy" beet.

Yield. Two experiments in Surrey (1948, 1949) and two in Suffolk (1949, 1950)* gave a mean response of 2.2 cwt sugar per acre-inch, the best responses being from 35 cwt to 44 cwt for 7.0 acre-inches in Surrey, and 31 cwt to 50 cwt for 5.5 acre-inches in Suffolk. The worst was in 1948, being from 67 to 68 cwt for 1.0 acre-inch, in Surrey.

Nine years' data from Woburn (1951-59) gave, on the *best treatments*, an average response of 2.7 cwt sugar per acre-inch, the average total response being near 6.4 cwt per acre, or about 12 per cent of the mean yield. Roots showed the same proportional response, sugar percentage at 18 being unaffected, but the yield of tops increased by 14 per cent. The best response in 1959 was from 60 cwt unirrigated to 88 cwt sugar with 7.3 acre-inches applied; there were good responses in 1951, 1952 and 1955 but responses were zero and even slightly negative in 1953, 1954, 1957 and 1958.

At Gleadthorpe in the period 1955-59, yield responses were very large in the dry years 1955 and 1959, there being little need for irrigation and little or no response in the intervening years. In 1955, the yield was increased from 18 to 63 cwt sugar using 7 acre-inches of irrigation, and in 1959 from 19 to 85 cwt sugar using 10 acre-inches of irrigation. The mean response per acre-inch was 5.5 cwt sugar over the five year period, the average total response being 23 cwt per acre, about 60 per cent of the mean yield.

In an experiment carried out at Wolverhampton (1957-59) no irrigation was required in 1958. The mean response per acre-inch was 2.0 cwt sugar, and the average total response 5 cwt sugar per acre over three years, or about 20 per cent of the mean control yield.

Over a five year period in the West Midlands (1955-59) yields from more than 80 fields have been recorded and compared with unwatered strips kept as controls. Average increases of 6.4 cwt sugar per acre have been obtained from each inch applied. The outstanding returns obtained from two very dry seasons 1955 and 1959, considerably influenced these figures, as little or no irrigation was carried out in 1958.

Belgian experience is that over 18 years the average response to irrigation was a 16 per cent increase in yield of sugar.

Virus disease has been the main source of variations in yield from year to year, and with better plant hygiene the response to irrigation may now be more consistent.

*1949 was a severe virus disease year.

6.2.3 Cereals

Few British data are available about techniques for irrigating cereals. Pot trials indicate that the best time to irrigate spring cereals appears to be between early stem elongation and ear emergence, but for winter wheat a slightly earlier application is more beneficial. In practice, it is usual to irrigate slightly before the early stem elongation stage, when the irrigation equipment is not required for other arable crops. The only experimental data available are from Woburn, where in most years irrigation was continued until July.

Spring barley. At Woburn⁽⁶⁻¹⁾ (1951-56) the major responses were in summers after dry springs. The six-year average of the *best treatments* was 1.8 cwt grain per acre-inch, with about two-thirds of this response at the higher of two nitrogen dressings (0.2 and 0.4 cwt N per acre). Only in two years (out of six) did irrigation give a response comparable to that obtained from doubling the nitrogen dressing. The best response at the lower nitrogen level was in 1951, from 22 cwt unirrigated to 29 cwt for 3.2 acre-inches.

The average yield of barley was increased by 56 per cent in a long term experiment⁽⁶⁻⁷⁾ in Denmark. In Holland⁽⁶⁻⁸⁾ increased yields of over 40 per cent have been reported.

Spring wheat. The Woburn average (1957-59) was 1.7 cwt grain per acre-inch, with one-and-a-half times this response at the higher of two nitrogen dressings (0.4 and 0.8 N per acre), suggesting—in contrast with barley—that wheat needs the extra water to respond to the extra nitrogen. The best response at the *upper* rate was in 1959, from 17 cwt to 30 cwt of grain for 4.7 acre-inches applied.

Cereals—general. Observation plots at Gleadthorpe and on farms in the West Midlands, have recorded increases of 50 per cent in years with dry spring from one or two irrigations of 1 to 3 inches at the late tillering stage; e.g. at Gleadthorpe in 1959, two applications of 1½ inches in late April and early June increased yields from 30 cwt to 44 cwt per acre. Further observations indicate that winter oats and winter wheat behave in a similar manner, e.g. 1½ inches applied to winter wheat at the end of April increased the grain yield from 28 cwt to 40 cwt per acre.

Quality. No positive evidence is available but some observations record that early irrigations increase the number of ear-bearing tillers, and may reduce the grain size. Irrigations between early stem elongation and flowering stage, however, increased the grain size.

6.2.4 Field beans

Vegetative growth is greatly increased by irrigation, and may produce embarrassingly tall crops.

Three years, 1957-59, at Woburn gave an average response of spring beans of 2.8 cwt grain (dry matter) per acre-inch without dung, and 2.5 cwt per acre-inch with 12 tons dung per acre; the crop only responded to dung when water supply was limiting growth. The best response was in 1957, from 11.8 cwt unirrigated to 25.6 cwt for 4.0 acre-inches; the worst, in 1958, was from 15.3 to 16.0 cwt for 1.0 acre-inch, both without dung.

A single result, for 1960, on *winter beans* at Woburn gave an increase from 26 to 40 cwt for 3.5 acre-inches—a rather surprising increase in a wet summer.

Grassland in North West Europe has been shown in numerous experiments to respond to irrigation. Of the major herbage crops, lucerne, a deep rooting crop, gives the least response (expressed as a percentage of the control yield) and white clover the greatest. The cultivated grasses are intermediate and show only small differences one from another.

6.3.1 Techniques

Most grasses and clovers respond to frequent irrigation. Experimental work has demonstrated that there is a progressive reduction in grass growth as the soil moisture deficit increases, and that the greatest yield per acre is obtained where the deficit is kept below 1 inch^(6-11, 6-12). Under grazing conditions, this is probably the most economic treatment to employ, but where the grass is being allowed a longer period of uninterrupted growth, perhaps for hay or silage, deficits of 1½ to 2 inches may be permissible. Irrigation should be applied as required throughout the growing season, though only rarely will use of the equipment be worthwhile before early April or after mid-September. The average annual irrigation need in large areas of England lies in the range 4 inches to 5 inches, with as much as 9 inches to 10 inches in some areas in some years.

Unlike most other crops, the efficiency of water use on grassland, measured in terms of dry matter response per unit weight of water applied, is greatest where the deficit is continuously kept small^(6-12, 6-17). For this reason, it is important not to exceed the deficit levels suggested above, and particularly not to extend the use of limited water supplies or equipment over too large an area.

The effect of irrigation on the response to nitrogenous fertilizers is uncertain. There are some conditions where the optimum level of fertilizer application is higher in the presence of irrigation⁽⁶⁻¹²⁾. In others, perhaps where irrigation increases the clover content of the sward, the optimum level may be unaltered or even depressed⁽⁶⁻¹¹⁾. In practice, however, the introduction of irrigation frequently encourages the farmer to increase fertilizer dressings which were previously inadequate. There is some evidence that higher levels of nitrogenous manuring increase the deficit range over which grass growth is unaffected by moisture stress^(6-11, 6-12).

6.3.2 Response

Yield increases in grassland irrigation experiments have varied from 1 cwt to 6 cwt of dry matter per acre-inch of water applied, according to season, sward, irrigation technique and grass management.

Mixed ley. At Woburn⁽⁶⁻¹²⁾ a three-year ley (sown in spring 1951) had two levels of nitrogen dressing, the standard application being 0.3 cwt N per acre applied in spring and then after every cut except the last. The average annual application was close to 2.0 cwt N per acre. Other plots were given half this rate. At the standard rate, the average response, 1951-53, was 4.4 cwt dry matter per acre-inch and the *best treatments* gave 5.2 cwt per acre-inch, made up (approximately) of 3.2 cwt grass and 2.0 cwt clover. The best year was 1952, with an increase from 56 cwt unirrigated to 88 cwt for 5.1 acre-inches; the worst was 1953, with an increase from 95 cwt unirrigated to 108 cwt for 5.6 acre-inches. At the half-standard rate of nitrogen application the same *best treatments* gave 5.9 cwt per acre-inch made up of 3.6 grass and 2.3 cwt clover.

In experiments in 1951 and 1953 at Jealott's Hill, Berkshire⁽⁶⁻¹¹⁾ the average two-year responses of grass/white clover leys were 19.0 cwt dry matter per acre in the absence of nitrogen, and 10.6 cwt per acre with sulphate of ammonia at 20 cwt in 1951, and 25 cwt per acre in 1953.

Similar work at Hurley^(6-13, 6-16, 6-17) in 1955-59 gave a mean response of 3.5 cwt dry matter per acre-inch without nitrogen fertilizer, for an average annual application of 10 inches. The average annual increase in dry matter over the five years as a result of irrigation was 33.6 cwt per acre, an increase in response of 70 per cent, ranging from an increase of 14 per cent in 1958 to 210 per cent in 1959. From 1956 onwards, nitrogen treatments were added; irrigation increased average yields from 46.5 cwt to 80 cwt per acre without nitrogen fertilizer and from 91 cwt to 125 cwt with an application of approximately 480 lb. nitrogen per acre per year. Nitrogen had no significant effect on the growth response per acre inch of irrigation in this experiment.

Pure grass stands. A six-year stand at Woburn (1954-59) had the same standard nitrogen treatment as before, with comparisons of half-standard 1954-56, and twice standard 1957-59. At the standard rate the six-year average response was 2.8 cwt dry matter per acre-inch, with a maximum increase in 1955 from 54 unirrigated to 82 cwt for 7.7 acre-inches. The minimum response was zero, in 1954, when all plots were irrigated to get the crop established in a dry spring. The relative responses to irrigation at half-standard, standard and twice-standard nitrogen rates were 0.81: 1.00: 1.17.

A two-year grazing experiment at Reading⁽⁶⁻¹²⁾, in 1955 and 1956, showed a bigger, but not inconsistent, range of differential response. In the absence of nitrogen the mean response was 2.7 cwt dry matter per acre-inch, but approximately 400 lb nitrogen per acre per season increased the response to 6.7 cwt per acre-inch.

In small-plot work at Reading⁽⁶⁻¹⁴⁾ during 1957 to 1959, nitrogen applications similar to the Woburn standard rate were used. Over the three years, the average response was 2.9 cwt of dry matter per acre inch, with a maximum increase in 1959 from 67 to 102 cwt for 9 acre-inches.

In Holland, experience is that irrigation of pastures increases dry matter yield by about 30 per cent, a slightly smaller nine-year average increase is claimed in Sweden, and a Danish experiment gave an increase of 85 per cent in protein from a ley where clover development was favoured by irrigation.

It is not easy to give a figure for the general response of herbage because so much depends on factors other than irrigation. In many parts of England, using an average application of 4 inches to 5 inches annually; 3 to 4 cwt per acre-inch is probably an underestimate of what a skilful farmer can achieve; this represents an average annual increase in yield of the order of a ton of dry matter per acre.

6.3.3 Other benefits

Irrigation can be valuable in establishing new grassland. It may also help to improve botanical composition^(6-12, 6-13) either directly by increasing the proportion of clover and better grasses, or indirectly by allowing and encouraging more intensive rotational grazing which again will usually favour the better grasses. The greater uniformity of grass production within and between seasons allows more accurate planning of stock numbers and can permit a reduction in any safety margin which has been allowed against the risk of drought. As a

result, the overall efficiency of grass utilization may well be increased; this greater uniformity of production is a very real and important effect. Thus in the Hurley experiment quoted above the ratio of the smallest to the largest annual yield with irrigation (with or without nitrogen) was 1:1.2, whereas without irrigation the ratio was 1:1.8 with nitrogen, and 1:2.5 without it.

Whilst both lucerne and cocksfoot leys are of great value in dry areas, the introduction of irrigation allows a change to others which are more flexible and which are easier to establish and manage. Catch-cropping can be carried out with more certainty. Perhaps the most important example on the dairy farm is the sowing of kale immediately following Italian ryegrass in June. In many areas this can be very risky if irrigation is not available. Introducing irrigation should therefore be the cause of a reappraisal of the cropping and stocking of the whole farm; its potential will not be fully exploited if it is merely superimposed on the existing system.

6.3.4 Utilization experiments

Few direct data are available on the effect on output of introducing grassland irrigation.

In the first year of a grazing experiment at Reading University⁽⁶⁻¹⁴⁾ the use of 4 inches of irrigation in 1960 resulted in an increase of 56 more grazing days (200 gallons of milk per acre) at one stocking rate, and 42 grazing days (110 gallons per acre) at a stocking rate one third lighter. These figures represent an increase of about a quarter better than the yields of the respective unirrigated treatments.

On a south Durham farm, use of town sewage effluent (with a fertilizing value also) on less than half of the acreage is given the credit for an increase in total farm output of 45 per cent. The grass is dried and fed as cubes to dairy cattle, or given in meal to pigs, or sold. Buying of concentrates was eliminated.

An A.I.C. report⁽⁶⁻¹⁶⁾ was able to record only general opinions from seven farms in 1956 and 1957. Irrigation of grass enabled higher stocking rates to be maintained at all times on a given area of grass, and the continuously available supply of grass prevented falls in milk yield which might otherwise have occurred before steps for supplementary feeding had been taken, a fall that is often irreversible.

Other commercial experience has suggested that milk output from grazing can be raised in dry areas by as much as four hundred gallons per acre if management and the dairy herd potential are sufficiently high.* This increase is greater than would be expected from the experimental work available, and may be partly due to further improvements in management stimulated by introducing irrigation. However, the increased output may be greatly assisted by the indirect benefits of irrigation (see Section 6.3.3) which are difficult to assess and can easily be under-estimated.

6.4 FRUIT

There have been relatively few experiments on the irrigation of fruit in England, but commercial growers are already applying sprinkler irrigation to fruit on a considerable scale. The figures and conclusions quoted below are based mainly on experiments at East Malling Research Station^(6-18, 6-24) together with experience of irrigation in other countries.

* The profitability of such a response will vary tremendously with circumstances

Fruit trees are deep rooting and can therefore tap water from the deeper layers of the soil profile^(6-18, 6-20, 6-23), so fairly long intervals can be left between irrigations. Small fruits, however, such as raspberries and strawberries are relatively shallow rooting and therefore may be likely to need irrigation frequently⁽⁶⁻²⁰⁾. Unlike arable crops, fruit plants are perennial and their fruit buds are as a rule initiated and borne on wood produced in the previous season; so irrigation benefits future as well as current crops. Indeed the benefits, particularly with tree fruits, are cumulative.

6.4.1 *Tree fruits*

Irrigation is likely to have beneficial effects on tree fruits on all soils with relatively low available water reserves. On deep soils, however, with water reserves of over 6 inches, water shortages are seldom serious⁽⁶⁻¹⁹⁾.

Irrigation is required in two phases:

- (i) to produce wood in the current year (mid-May to end of June);
- (ii) to swell the fruit (mid-July to August or September).

With irrigation, the permanent framework of the tree grows much faster with a consequent increase in yield in future years. Where trees are cropping heavily, soil moisture needs to be maintained at a higher level than when cropping is light.

With apples, fruit size does not appear to be affected until about 70 per cent of the available water has been used, although, under dry conditions, vegetative growth may be checked either partially or entirely before this. Hence, under certain climatic conditions, irrigation may be used to control both vegetative growth and fruit size or fruit size alone.

Trees with roots 5 feet deep in a medium loam (brickearth type soil) could have as much as 10 inches of available water; irrigation would then not be necessary to maintain fruit size until a deficit of 7 inches was reached. For trees with roots 5 feet deep in a loamy sand, only 5 inches of water would be available and irrigation would be required at a deficit of $3\frac{1}{2}$ inches. Since some margin of safety is required to compensate for inaccuracies in the estimations of available water and moisture deficit and to allow for any time lag before irrigation can be applied over an entire area, irrigation should begin at a deficit value at least 1 inch less than that theoretically permissible. For young trees the deficit should not exceed 50 per cent of the available water⁽⁶⁻²⁴⁾.

When irrigating, it is better to return almost the whole profile to field capacity at each application rather than to give smaller but more frequent irrigations, for the latter would encourage shallow rooting. But where deficiency is restricting growth or cropping, some water is better than none.

It appears that extra nitrogen can reduce the effect of a water deficit in tree fruit but not in small fruit crops. It is possible to apply fertilizers to fruit crops in the irrigation water, but this is rarely done because the fertilizers are normally applied long before irrigation is required.

Irrigation can make it possible to use grass swards in orchards on relatively poor or shallow soils, with consequent improvements in soil structure and ease of management; the supplementary watering offsets the risk of severe competition for water and nitrogen.

Yields. The effect of irrigation on the yield of tree fruits tends to be cumulative, because of the increases in tree size. In experiments on a sandy soil, increases in

yield of apples of 20—50 per cent were obtained; current research suggests that, within limits of excessive wetness and dryness, the response per acre-inch applied is approximately linear.

In an experiment with young Laxton's Superb apple trees, on a sandy soil at East Malling, the total yield from irrigated trees over the eight years 1953–60 was about 840 bushels per acre more than from unirrigated trees (a bushel = 40 lb). The total water applied was 29 acre-inches (i.e. an average of about 3.6 acre-inches per year). Thus the average increase was about 29 bushels per acre-inch⁽⁶⁻¹⁰⁾. This striking increase was obtained on a soil with relatively low reserves of available water. It must be stressed that responses will vary according to soil, seasonal and other factors.

Fruit size. The best prices are obtained for dessert apples of 2½–3 inches in diameter. Irrigation in some years may increase the number of apples within this size grade by about 40 per cent⁽⁶⁻¹⁰⁾.

Colour and flavour. Laxton's Superb apples showed no differences between irrigated and unirrigated trees in fruit colour, or in flavour (as tested by a tasting panel). In a trial in which lavishly irrigated young Cox's Orange Pippin trees made excessive growth, the fruits on these trees were too large and poorly coloured⁽⁶⁻¹⁰⁾. If, however, irrigation is regulated to avoid excessive growth, fruit colour and flavour will not suffer.

There is insufficient evidence to show whether there is any difference in the responses of different varieties and species of tree fruit crops to irrigation, but any difference would probably be in degree not in kind.

6. 4. 2 *Small fruits*

Unlike tree fruits, most small fruits are comparatively shallow rooted and there is a danger, in dry years, of a great reduction in fruit yield. Further, the restricted vegetative growth leads to reduced yields in the following year. Increase in the vegetative growth and improvement in the quality and size of the fruit have been obtained by irrigation not only on poor soils but also on rich ones.

Irrigation is probably desirable when 50 per cent of the available water has been used⁽⁶⁻¹⁴⁾.

Raspberries. In irrigation experiments with two varieties of raspberry, on a deep loam at East Malling⁽⁶⁻¹⁴⁾ the average response over three years has been between about 30–40 per cent increase in yield. The average gain was 1.3 tons per acre per year, or 0.10 to 0.15 tons per acre-inch. The increase comes both from the greater production of cane in the previous year, and the increased fruit size in the current year.

Blackcurrants. Irrigation experiments with blackcurrants at East Malling⁽⁶⁻¹⁴⁾ showed increased yields from irrigation of 35–55 per cent, i.e. an extra 0.91 to 1.43 tons per acre, from two differing treatments, averaging about 0.1 tons gain per acre-inch.

Strawberries. Strawberries are relatively shallow rooted and are the first fruit plants to suffer in times of drought; wilting is not uncommon. Irrigation at soil moisture deficits as low as 1–1½ inches is often beneficial. Excessive irrigation in humid conditions may, however, lead to increased risk of losses from Botrytis rot.

The average increase in yield of irrigated over non-irrigated strawberry plants in fifteen experiments at East Malling was 18 per cent, with plants spaced in the

row. Commercial growers often allow runners to root within the rows thus forming matted rows. Under such conditions the yield from irrigated plots may be as much as 40 per cent higher than from non-irrigated plots⁽⁶⁻²²⁾. The fruits of irrigated strawberry plants tend to ripen slightly later than those on unwatered plants: this is of little importance for maincrop varieties, but may be of significance for early varieties.

In the East Malling experiments quoted above⁽⁶⁻²²⁾ the response to irrigation varied from -3 cwt to +21 cwt per acre, or -3 to +48 per cent. The average benefit was 6.7 cwt or 18 per cent, from only 1½ inches a year.

6.5 VEGETABLES

6.5.1 General

In recent years the irrigation installation has come to be regarded as part of the normal equipment of a market garden. Experience dictates that most vegetables should be kept growing steadily throughout their field life, and in dry weather judicious watering can help to avoid growth checks which may reduce yield and impair quality. With most vegetables irrigation is undesirable immediately after sowing or while the plants are in the young seedling stage; impact of the comparatively large drops produced by most commercial irrigation equipment can damage the surface structure of many soils and so adversely affect the germination and establishment of seedlings. Adequate soil moisture at this time may be ensured by irrigation during cultivation prior to preparing the seed bed. Irrigation equipment may also be used to soften caked soil with a comparatively small quantity of water so that roots or bulbs can be harvested. Irrigation can facilitate cultivations between successive crops, thus speeding up the rotation and reducing the length of time that valuable market-garden land is left vacant; a spell of dry weather may so delay preparation of the soil after clearance of a summer crop that the subsequent crops cannot be satisfactorily established.

Irrigation⁽⁶⁻²⁵⁾ has been shown to affect the quality of vegetable produce—in some instances beneficially, e.g. improvement in tenderness and palatability of turnips and lettuce—or detrimentally, e.g. reduction in flavour intensity in carrots. Little work has been published concerning possible effects on keeping quality, but irrigated produce usually has a plump, attractive appearance which is of obvious benefit in retail selling.

So far intensive research to determine the best watering treatments has been confined to only a few of the major crops. The complexity of the responses affords little hope of finding a simple watering procedure applicable to all vegetable crops. With market-garden crops, watering must be regarded in much the same way as fertilizer application—that is, regulated according to the crop and its particular needs. Some crops have been found to respond to watering in terms of increased marketable yield whenever there was an appreciable soil moisture deficit at any time during their growth; others gave increased yield only when watered at certain stages of their growth. In the following section two examples of contrasting behaviour are given.

Irrigation cannot compensate for bad growing, and with short-lived plants like most vegetables, the provision of adequate soil moisture is only one of a number of essential conditions, all of which must be satisfied in order to obtain a good yield of high quality produce suitable for market.

6.5.2 Examples

1. *Peas*⁽⁶⁻²⁴⁾. The effect of irrigation on peas depends upon the stage of growth of the plants when the water is applied. Watering before the flowers appeared increased the growth of haulm, but this was not accompanied by an increase in marketable yield, whereas watering after flowering resulted in marked yield increase. A single application of half an inch of water when the pods were beginning to swell raised the yield of pods from four to six tons per acre; no further increase resulted from two additional waterings of one inch each *before* flowering.

In these experiments the soil moisture content was raised to field capacity during seed-bed preparation. Failing this, and also in a dry season, watering before flowering would be expected to increase yield. Furthermore, where mechanical harvesting is practised on light soil with poor water-holding capacity, some irrigation before flowering may be necessary to produce sufficient length of haulm to enable the machines to operate efficiently.

Peas for canning and freezing are processed largely according to Tendrometer* values of shelled samples which are roughly indicative of maturity. In experiments, post-flowering irrigation delayed the rise of Tendrometer reading, and therefore prolonged by one or two days the period during which the produce was acceptable to the freezers or canners.

2. *Early summer cauliflowers*^(3-23, 4-25). One commercial method of producing plants for setting out in the spring is to sow in the previous autumn and raise the plants under unheated glass. Water is given only sparingly to keep the plants small and avoid frost damage. Experiments have shown, however, that this practice can cause a reduction in eventual yield. Weekly watering during the winter increased the mean diameter of marketable curds by about half an inch, even when no irrigation was carried out after planting in the field: the winter watering did not increase damage from frost, and the comparatively large plants produced could be planted out satisfactorily provided the field soil moisture content was near to field capacity.

Field experiments have shown that for maximum yield the soil moisture deficit should not be allowed to exceed half an inch during the five or six weeks from planting out until mid-April, and thereafter one inch on heavy soil or half an inch on light soils. Such watering gave up to 60 per cent increase over the six tons per acre yielded by unirrigated controls, depending upon the dryness of the season. Worth-while results have been obtained, however, with less frequent watering. In a dry season, one inch of water applied a few days before cutting began gave 35 per cent increase in marketable weight and increased average curd diameter by half an inch. With one variety of summer cauliflower, some attempt has been made to elucidate the expected interaction between plant spacing and watering treatment on a fertile soil. When yield was assessed in tons of marketable produce per acre, at spacings closer than twenty-four inches square, there was a progressive reduction in yield where irrigation was not used. Where irrigation was used at these spacings, it was possible to maintain yield

*One of several available instruments which measure the resistance of the peas to imposed mechanical stress.

fairly constant. When, however, yield was assessed in terms of crates of marketable curds per acre (the manner in which this crop is usually sold) the highest marketable yield was obtained at the closest placing *provided that the crop was irrigated*⁽⁶⁻²⁷⁾. This higher yield was made up of a larger number of smaller marketable curds than that produced at wider spacing.

6.5.3 Response

The yield and quality of most vegetables can be improved by judicious irrigation. Increase in soil moisture commonly results in increased foliage production, accompanied by an increase (though not usually a *proportional* increase) in yield of marketable produce.

Response to the application of a given volume of water has depended especially on the stage of plant growth when water was applied. With turnips⁽⁶⁻²¹⁾, and peas⁽⁶⁻²⁶⁾, growth stages have been demonstrated at which irrigation increased foliage production but not marketable yield, and other stages when yield was increased by the same, or even a smaller, amount of irrigation. With cauliflowers⁽⁶⁻²⁷⁾, and carrots⁽⁶⁻²⁸⁾, no such moisture sensitive growth stages have been observed.

The largest responses in terms of marketable plus unmarketable yield is likely to result from preventing the accumulation of an appreciable deficit at any time during the crop life. This is hardly practicable. Those crops which give satisfactory marketable yields following irrigation only at particular growth stages, or with quantities of water less than the current moisture deficit, afford opportunity of obtaining the greatest return for the expenditure of the smallest amount of water.

Different soils have different available water capacity and also vary in their conduction of water to the region of the roots. Under identical weather (deficit) conditions, crops on different soils experience different soil moisture tensions, and therefore vary in their response to identical irrigation. This is especially likely to affect fast-growing plants such as vegetables. The available water content of certain soils has been increased by dressings of dung⁽⁶⁻³⁰⁾. Moreover, the extra water was held mainly at very low tension and was, therefore, *readily* available to plants. This may explain the response of some vegetables to dung being greater than would be expected on purely nutritional grounds.

It is difficult to assess yield increase from information supplied by growers because they do not usually leave control areas unirrigated. Under experimental conditions in different parts of the country, increases have been obtained with many different vegetable crops, e.g. summer cauliflower (increase of three tons per acre over the six tons yielded by unirrigated controls), peas (two tons increase over four), self-blanching celery (eight tons over thirty), and carrots (two tons over fourteen). Irrigation has sometimes made the difference between a complete crop failure and a satisfactory yield (e.g. lettuce, spinach and cauliflower).

The magnitude of yield increases from irrigation depends, of course, upon the weather. When, in wet seasons, comparatively small amounts of water have been applied in attempts to obtain maximum yield by providing maximum available soil moisture, yield depressions have sometimes resulted. Yield depression has also resulted under experimental conditions when the seed-bed was watered after sowing with the object of improving germination. Watering certain crops in the seedling stage has had a similar bad effect.

In addition to the crops mentioned above, which have been the subjects of properly controlled experiments, many other vegetable crops are commonly and increasingly irrigated by growers, who evidently find that the results justify the practice. These crops include runner beans, marrows, salad onions, cabbage and mint; indeed, the yield of almost every vegetable crop has, in suitable seasons, been increased by judicious irrigation.

As a general rule, in most market garden districts, irrigation can be beneficial to vegetables at some time or other in most years. This benefit can take the form of a substantial yield increase, or of improved quality of produce, or by bringing about germination, or facilitating harvesting operations or enabling a crop to be placed on the market at a time when non-irrigated crops could not be produced. The cash value of some of these benefits, though undoubtedly substantial, would be very difficult to estimate.

In an economic survey⁽⁶⁻³⁴⁾ of a sample of 32 Vale of Evesham holdings, it was found that the average profit margin of holdings with irrigation facilities was more than six times as high as on other holdings. Production on irrigated holdings was two-and-a-half times that on unirrigated holdings.

6.6 OTHER ASPECTS

6.6.1 *Protection against frost*

Damage by spring frost to fruit blossoms and other crops, including vegetables, may be prevented or reduced by the use of overhead sprinkler equipment. It can give protection in either of two ways, (a) indirectly, by wetting the soil and so increasing its efficiency as a reservoir of heat, or (b) directly, by giving out latent heat of freezing when water is continuously sprinkled over plants during frost.

(a) *Indirect protection.* Wet and compact soil is a better conductor than dry and loose soil hence there is greater heat absorption on a warm day and greater outward transfer of heat during a relatively cold night together with a cooling effect due to evaporation. The combined effect is that the air above wet soil on a frosty night, is about 1° or 2°F warmer than that above dry soil^(6-37, 6-38). This method is therefore only useful when the frost is of marginal severity, and for low growing crops such as strawberries or potatoes. Successful protection of early potatoes was obtained on three experimental sites in the West Midlands in 1961. On 26th May the screen temperature was 29°F and the grass minimum measured nearby was 22°F. An increase in yield from 2.8 to 7.3 tons per acre was obtained when the crop was lifted on 21st June.

(b) *Direct protection.* If water is sprinkled continuously over a crop during a frost, at a rate fast enough to ensure that a new supply of water is continuously freezing on the plants, the release of latent heat of freezing is sufficient to keep the temperature of the plant at or near 32°F, at which temperature it is undamaged^(6-35, 6-36, 6-38, 6-40). This method of protection is being used for thousands of acres of apples in the Adige Valley of Northern Italy, and on a considerable scale in Germany, Belgium, Holland and the U.S.A., and to a limited extent in England, particularly for the protection of fruit. It can also be used to protect vegetables and flowers and also crops under frames and cloches provided the plants can stand the load of ice. The soil must be able to absorb the amount of water applied, for although the rate of application is usually less than half that

of normal irrigation, sprinkling may be applied for several hours on successive nights if successive frosts occur.

The rate of sprinkling required depends on the severity of frost. In experiments at East Malling^(6-34, 6-37), the following relationship was found, for apples in full bloom, and conditions of radiation frost with winds of 2 m.p.h.

Precipitation rate (inches per hour)	0.08	0.16	0.24
Protection given in frost of screen minimum (°F) ..	26.0	23.5	21.5

It is difficult to vary the sprinkling rate according to air temperature, so in practice a rate is chosen that protects the particular plant from a reasonable amount of frost and is still economical. In general, a sprinkling rate of between 0.1 inches and 0.13 inches per hour is likely to be adequate under English spring conditions.

Any equipment that can apply the required amount of water and that operates reliably in a frost can be used, provided the sprinklers rotate not less than once per minute. Small rotary sprinklers, spaced at about 40 to 60 feet apart are the most common. It is important that the nozzle sizes and pressures should be correct, to achieve reasonably uniform distribution, giving not less than the necessary minimum precipitation rate at any point. In orchards the sprinklers must be raised above the trees on standpipes. Sprinkling should be started when the temperature falls to 32°F, continued throughout the frost, and ended as soon as the temperature rises above 32°F^(6-34, 6-35, 6-37).

Automatic frost protection systems are possible where the pump is driven by an electric motor, the switching being initiated by adjustable contacts in a thermometer, so avoiding night labour. It is not easy to start diesel and petrol engines in this way, but such engines can be automatically switched off after danger has passed. Where manual operation is used a good alarm thermometer is essential, to warn the operator when to start the pump. The whole system of pipes and sprinkler equipment should be tested every day and left drained so that it cannot freeze up.

The frequency and duration of spring frosts vary according to site and season, but the need in many low-lying orchards might be for protection for 2 to 6 hours on say 2 to 6 nights, i.e. a total usage of $\frac{1}{2}$ to 3 inches of water spread over 3 weeks in spring. At this time the demand for water for ordinary irrigation is low.

Few growers would install irrigation equipment solely for frost protection, but where irrigation is also used in summer the equipment, suitably modified, can be used in spring to protect whatever area one setting of the available sprinklers can cover.

6. 6. 2 *Irrigation and fertilizer practice*

The introduction of irrigation may require changes in fertilizer practice. In the long term it will normally be necessary to increase fertilizer dressings because of increased removal of nutrients by the crop. However, in some circumstances irrigation may increase the availability of soil reserves and applied fertilizer, so that dressings can be profitably reduced. In cases of doubt, the farmer or grower should seek specialist advice, although considerable research is still needed to determine the most appropriate fertilizer practices. This also applies to the micro-nutrients whose availability may sometimes be affected by irrigation.

Controlled irrigation, applying the correct amounts of water at the right time, is unlikely to increase the leaching of nutrients from the soil unless considerable rainfall occurs shortly after the irrigation, but excessive irrigation, like excessive rainfall, can leach some nutrients out of the soil; this may sometimes justify heavier fertilizer dressings. There is some evidence that generous manuring, particularly with nitrogenous fertilizers, may enable some crops to withstand slightly higher soil moisture deficits.

6.6.3 Spreading fertilizers

Soluble fertilizers can be applied using irrigation equipment and on some holdings this may result in a reduction in the cost of fertilizer handling. This is done to a considerable extent in glasshouses, and occasionally on vegetable crops in the field. Special equipment injects a dilute solution of fertilizer into the irrigation water. Care is needed to avoid scorching the foliage, and the use is restricted to periods when both fertilizers and irrigation are required. Better crop growth has been claimed as an additional benefit but little experimental work has yet been carried out on this aspect.

6.6.4 Disposal of animal manure

A method of spreading organic manures by overhead irrigation equipment had recently been developed. The organic residues are finely broken up and pumped, with the liquid manure diluted with water, through irrigation equipment of the rain gun type. Considerable saving of labour and more efficient use of farmyard manure are claimed.

6.6.5 Pests and diseases

Experimental work has shown that there are some interactions of irrigation with pests and diseases, particularly where wet or dry conditions upset the balance between plant and disease or pest. If irrigation is excessive, or if wet conditions follow irrigation, some fungus diseases such as grey mould (*Botrytis spp.*) or potato blight (*Phytophthora infestans*) may spread more rapidly. On the other hand, the incidence of common scab (*Streptomyces scabies*), bacterial soft rots and potato blight in potato tubers has been shown to be decreased by irrigation, under certain conditions.

The misuse of irrigation has increased the incidence of pink rot (*Phytophthora erythroseptica*) in potato tubers, and club root (*Plasmodiophora brassicae*) in *Cruciferae*. Experimental work has shown that attacks of weevil larvae (*Sitona spp.*) on the nodules of peas and beans have been reduced by irrigation; the effects of wireworms (*Agriotes spp.*), and of Cereal Root Eelworm (*Heterodera avenae*) are less under irrigation. Observations have indicated that irrigation during the early flowering of peas has decreased the amount of damage by pea moth (*Laspeyresia nigricana*); and the number of aphids present (*Myzus persicae*, *Aphis fabae*, *Brevicoryne brassicae*) were less in irrigated crops as compared with non-irrigated. On the other hand, overhead irrigation has increased the spread of chrysanthemum leaf eelworm (*Aphelenchoides ritzema-bosi*). In general, these are secondary effects, but they are worth further study.

6.6.6 Quality of water

Much surface water is polluted to some degree by sewage, sewage effluent or industrial wastes and for many years legislation has been directed towards the improvement of the condition of rivers.

In the past, not much attention has been given by farmers in this country to the quality of water used for irrigation. Broadly, if water has been available it has been used. Only where it has been obviously doubtful has the quality been considered before use. If detrimental effects occur, then at some stage the quality of the water might be suspected, but such cases do not appear to be common. Salt in the water may be a hazard particularly where the extraction rate from rivers is as high as it was in some coastal areas in 1959. Use of sewage effluent raises certain difficulties in relation to soils, animals, crops and public health, and the extent to which it may be used in the future is very problematic. Certain salts may corrode equipment and detergents remove grease. Hormone and chemical sprays may be a danger if they can get into irrigation water. On the other hand two inches of water having a hardness of 10 degrees would add about 56 lb of lime per acre: such amounts, though small in relation to normal agricultural dressings, could have some influence in the course of repeated dressings. As demand for irrigation water grows, however, the use of doubtful sources is likely to increase and it is probable that much more attention will have to be given to possible detrimental effects, including potential health hazards, of water with varying kinds and degrees of pollution.

If spray irrigation is used, the temperature of the water will be practically the same as that of the air and little different in temperature from rain. It may therefore slightly cool the leaves during the irrigation period; but will hardly effect the soil temperature, except at the surface. The water will become aerated by spraying even if it is not aerated already.

REFERENCES

- 6.1 ROTHAMSTED EXPERIMENTAL STATION. *Annual Reports* 1951-1960.
- 6.2 M.A.F.F. GLEADTHORPE EXPERIMENTAL HUSBANDRY FARM. *Annual Reports* 1955-1960.
- 6.3 NORTH, J. J. Irrigation of Farm Crops. *J. R. Agric. Soc.* 1960, 121.
- 6.4 HARWARD, M. E. *et al.* Effect of soil moisture tension on potato Bacterial Soft Rot. *Soil Sci. Pro. Am.* 1951, 20, 59-65.
- 6.5 HERRMAN, F. J. Irrigation a means of ensuring and increasing potato yields. *Kartoffelbau* 1955, 6, No. 3, 52-3.
- 6.6 ——— Report from Crops Experimental Station Jutland. *Stat. Fors: Plantekultur* No. 565, Jan. 1957.
- 6.7 HEICK, F. Yearly Trials with artificial watering of field crops, *Tidsskr. Planteoul.* 1952, 55, 433-48.
- 6.8 BAARS, C. Overhead irrigation of sandy soils sensitive to drought. *Landbouwk. Rijschr. Wageningen* 1954, 66 (9), 625-33.
- 6.9 N.A.A.S WEST MIDLAND REGION. Unpublished Data.
- 6.10 AGRICULTURAL IMPROVEMENT COUNCIL, LAND MANAGEMENT COMMITTEE. Irrigation Investigation (unpublished information).
- 6.11 LOW, A. J. and ARMITAGE, E. R. Irrigation of grassland. *J. Agric. Sci.* 1959, 52, 256.
- 6.12 MUNRO, I. A. Irrigation of grassland. The influence of irrigation and nitrogen treatments on yield and utilization of a riverside meadow. *J. Brit. Grassland Soc.*, 1958, 13, 213.
- 6.13 PENMAN, H. L. *Annual Report*, 1961, Experimental Station, Rothamsted, pp. 33-38.
- 6.14 TAYLER, R. S. Unpublished information, 1961, Reading University.
- 6.15 WILLIAMS, T. E. *et al.* *Experiments in Progress* No. 9, 1956. Grassland Research Institute, Hurley, Berkshire.

6. 16 WILLIAMS, T. E. *et al. Experiments in Progress No. 11*, 1959. Grassland Research Institute, Hurley, Berkshire.
6. 17 WILLIAMS, T. E. *et al. Experiments in Progress No. 12*. Grassland Research Institute, Hurley, Berkshire.
6. 18 COKER, E. G. *Root Studies XII*. Root systems of apples on Malling rootstocks on five soil series. *J. hort. Sci.*, 1958, 33, 71-79.
6. 19 GOODE, J. E. Irrigation trials with apples, raspberries and black currants at East Malling. Unpublished data, 1960.
6. 20 ROGERS, W. S. Fruit Plant Roots and their environment. *Rep. XIII Int. Hort. Congress*, 1952, 288-292.
6. 21 ROGERS, W. S. An apple irrigation trial, using soil moisture meters. *Ann. Rep. East Malling Res. Sta. for 1938*, 39, 118-126.
6. 22 ROGERS, W. S. Strawberry irrigation trials at East Malling. Unpublished data, 1960.
6. 23 ROGERS, W. S. and BOOTH, G. A. The roots of fruit trees, *Scientific Horticulture* 1960, 14, 27-34.
6. 24 ROGERS, W. S. and GOODE, J. E. Irrigation requirements of fruit orchards. *Ann. Rep. East Malling Res. Sta. for 1952*, 53, 171-173.
6. 25 Results of experiments carried out at Luddington, Efford, Stockbridge House and Rosewarne Experimental Horticulture Stations by N.A.A.S. Staff in collaboration with National Vegetable Research Station, Wellesbourne. Data published in Annual Reports of each station for 1956 to date. Combined Report in course of preparation.
6. 26 SALTER, P. J. Irrigation of peas. *Rep. nat. Veg. Res. Sta. Wellesbourne for 1959*, 1960.
6. 27 SALTER, P. J. Irrigation of early summer cauliflowers in relation to stage of growth, plant spacing and nitrogen level. *J. hort. Sci. (In the press)*.
6. 28 SALTER, P. J. Effects of different irrigation treatments on growth and yield of early summer cauliflowers. *J. hort. Sci.* 1959, 34, 23-31.
6. 29 SALTER, P. J. Effects of different soil moisture conditions during the seedling stage on the growth and yield of early summer cauliflowers. *J. hort. Sci.*, 1961, 35, 239-248.
6. 30 SALTER, P. J. and HAWORTH, F. The available water capacity of a sandy loam soil, Part 2, The effects of farmyard manure and different primary cultivations. *J. soil Sci. (In the press)*.
6. 31 STANHILL, G. Effects of soil moisture status on the yield and quality of early turnips. *J. hort. Sci.* 1958, 33, 108-118.
6. 32 STANHILL, G. Irrigation of carrots, *Rep. nat. Veg. Res. Sta. Wellesbourne for 1956*, 47.
6. 33 STANHILL, G. Irrigation of self-blanching celery. *Rep. nat. Veg. Res. Sta. Wellesbourne for 1957*, 37.
6. 34 FEKETE, E. B. A study of the functional layout of some mixed horticultural holdings in the Vale of Evesham (1955/56). Selected papers in *Agricultural Economics*, 1958, 6 University of Bristol.
6. 35 ROGERS, W. S. MODLIBOWSKA, I., RUXTON, J. P. and SLATER, C. H. W. *J. hort. Sci.*, 1954, 29, 126-141.
6. 36 ROGERS, W. S. *The Commercial Grower*, 1957, 834-5.
6. 37 ROGERS, W. S. *The Grower*, 1957, 47, 984-5.
6. 38 ROGERS, W. S. and MODLIBOWSKA, I. International Horticultural Congress 1958, Nice, Proc. XV.
6. 39 SLATER, C. H. W. and ROGERS, W. S. Unpublished data.
6. 40 ROGERS, W. S. and MODLIBOWSKA, I. *The Grower*, 1961, 55, 658-661.

SECTION 7

ECONOMICS OF IRRIGATION

7.1 THE INDIVIDUAL FARMER

7.1.1 *General*

The costs and returns from irrigation have been examined in Sections 5 and 6. Costs may vary from as little as £1 to as much as £10 per acre-inch, depending, in particular, on whether "free" water is available or expensive source works are needed, and on the length of main required for a given irrigated area. Similarly, returns may vary, from very little on a moisture-retaining soil in a wet part of the country to a considerable amount on some light soils in the driest areas of the south-east.

In assessing the likely effects of irrigation on individual farms, the characteristics of the farm and the farmer must be considered. Results, and therefore returns, depend in the first place upon the capacity of the farm's water supply and irrigation equipment in relation to crop requirements. In the second place, they depend on the farmer's knowledge of when to irrigate in relation both to the general weather situation and to the needs of particular crops, and the care with which irrigation is carried out. In the third place they depend upon the general level of farm management, e.g. fertilizer use and cultivation practices. Irrigation demands good management and there is no substitute for it; incorrectly applied, irrigation is merely a further unnecessary cost. It should only be considered where the standard of management is high; this is particularly true for grass, where irrigation is only likely to pay under intensive management. Again, the practice of irrigation may require modifications in field layout and reorganisation of stocking practices, all of which may add to the capital costs.

The question "Does irrigation pay?" is therefore impossible to answer without taking into account the circumstances of the farm and the farmer. Clearly the results given in Section 6 show that irrigation ought to pay on many farms over a large part of the country, provided water can be made available cheaply.

7.1.2 *Financial returns*

The possible financial return may be illustrated by the yield increases obtainable from potatoes. An average of 3 tons per acre together with a higher percentage of ware would be, in the eyes of many people with irrigation experience, a modest achievement. This should add at least £40 per acre to the return from the crop after allowing for additional harvesting costs. This compares with a cost of possibly £7 per acre with "free" water and perhaps £25 at the highest likely level. Returns from fruit or vegetable irrigation can be considerably higher. A crop like sugar beet, however, gives a lower return: an average increase of two tons per acre, worth £10 per acre, would be a typical increase. This would cover the cost with "free" water, but expensive source works would not be justified.

Thus, the actual crops grown, or which could be grown using irrigation, will clearly have a considerable effect on whether irrigation on the individual farm is economically worthwhile. Likely yield increases and their value in the years

that irrigation is required are given below (Table 7.1); extra harvesting and processing costs incurred because of the additional yield have been deducted from the gross value to give the net value of the increase, before deduction of irrigation costs. Insufficient evidence is available for these figures to be classed as true averages, but they indicate the likely order of benefit to be derived from different classes of crop in the years in which there is irrigation need (Fig. 1).

TABLE 7.1

Likely responses of crops to irrigation (when applied correctly under suitable conditions)⁽¹⁾

Crop	Amount of Irrigation inches per year	Increase in yield per acre	Increase- per cent	Increased value per acre (£)(2)
Early Potatoes(3)	2	2-3 tons	50	50-80
Maincrop Potatoes	4	3-4 tons	40	40-50(4)
Sugar Beet	4	2½ tons	25	16
Spring Cereals	2	3½ cwt(5)	15	3½
Spring Beans	3	8 cwt	50	10
Peas (freezing or canning)	1	10 cwt	30	20
Peas (fresh in pod)	1	20 cwt	30	60(6)
Grass	5	10-30 cwt(D.M.)	20-60	10-30
Dessert Apples (shallow soil)	3	75-125 bushels	30-50	100(4)
Raspberries	4	12-20 cwt	30-50	80
Blackcurrants	4	12-20 cwt	30-50	90
Strawberries	2	8-16 cwt	20-40	65
Cauliflower (summer)	2	60 cwt(7)	60	150(8)
Celery (self-blanching)	4	160 cwt	25	300(8)
Lettuce (summer)	2	80 cwt(7)	20-40	160(8)

(1) These are the likely responses averaged over the years in which irrigation is required in a particular area.

(2) After allowing for extra harvest and post-harvest costs.

(3) Mid-June to mid-July lifting.

(4) Including an allowance for increased size.

(5) Considerably greater responses have been claimed commercially.

(6) Market prices of fresh vegetables vary widely according to quality and supply and demand; the figures quoted should therefore be taken only as examples—they are not averages.

(7) The effect of irrigation on marketable yield of vegetables is probably even more dependent upon weather than is the case with other crops.

Costs per acre at five levels of application (from 1 to 5 inches per year) are given in Table 7.2, and at four levels of water cost (from 0 to 4s. 0d. per 1000 gallons), assuming average variable costs of 22s. 0d. per acre-inch. For simplicity, it is assumed that each acre irrigated requires a capital expenditure of £25 (equivalent* to 63s. per annum in interest and depreciation), whatever the annual water application. For horticultural crops grown on a small scale, operating costs may be substantially higher than those assumed here for farm-scale irrigation. This does not, however, affect the priorities given below.

*Assuming an expenditure of £20 on portable equipment and of £5 on fixed equipment.

TABLE 7. 2

Total cost of irrigation per acre (shillings)

Water applied per annum— inches	Cost of water per 1000 gallons			
	Nil	1s. 0d.	2s. 6d.	4s. 0d.
1	85	107	141	180
2	107	153	219	287
3	129	197	299	401
4	151	241	375	513
5	173	287	455	625

7.1.3 Priorities

By comparing the figures in Table 7. 2 with the annual water requirements of various crops and the financial benefits received from irrigation (Table 7. 1), it is clear that in the drier areas:

1. Fruit, vegetables, potatoes and peas justify irrigation even with water at 4s. 0d. per 1000 gallons.
2. Sugar-beet and field beans are only likely to be worth irrigating if water is available at low cost.
3. Grass will be worth irrigating with water at low cost, provided the stocking rate is increased sufficiently to utilise the increased yield.
4. Spring cereals will only justify irrigation if "free" water is available and equipment has been provided for other purposes. Even with a storage reservoir, water for cereal irrigation will be effectively "free" for use on cereals in the spring if the reservoir can be replenished with "free" water before water is needed for other crops.

Thus, on the basis of these figures, the order of priority where water is limited would be approximately as follows:

Vegetables
Fruit
Potatoes
Grass, if intensively used
Sugar beet
Field beans
Cereals

This type of costing implicitly assumes that unlimited water is available when required at the stated price. If, however, the supply is from a reservoir, the total amount available will probably be limited. Thus, in dry years, when the responses to full irrigation will be largest, the amount of water that can be applied may be less than could be profitably used. In wet years, on the other hand, all the available water may not be used.

Much more research is required into the best methods of utilising given quantities of water in different types of season, and on farms with different cropping

patterns. In particular more information is required on the responses of crops to sub-optimal amounts of irrigation in dry years. Without this information it is impossible to make any proper assessment of the true profitability of irrigation schemes involving storage reservoirs. Similar considerations apply, though less obviously, to many schemes where there is a fixed charge for water or where water is "free"; for, if the collective demand exceeds the available supply, some limitation will have to be imposed on consumption.

If water is limited, not in the sense of the total quantity available for annual use, but in the sense of the quantity available at any one time because of restricted supplies (e.g. flow or borehole output), similar problems arise. It will then be necessary to compare crops which will be competing for water at the same time of the year, as shown in the calendar (Appendix A).

7.1.4 *Other benefits*

The farmer not only benefits from higher yields from irrigation, but also from higher prices for out-of-season production, and during periods of short supply caused by drought. This can be of paramount importance in vegetable production; for example, the seasonal price fluctuations that occur with crops such as lettuce are well known, and after the dry 1955 season the farm price of potatoes rose to £40 per ton compared with an average figure of about £12 per ton. This means that irrigation of potatoes on light soils that year could have given an increased return of as much as £200 per acre. Irrigation results in a more even flow of produce, often of improved quality, which is of particular value when producing crops on contract for freezing and canning, and, consequently, contractors tend to favour farmers using irrigation.

Irrigation can make it possible to prepare a seed bed and sow a crop where, without it, the crop would almost certainly fail, or perhaps could not be sown at all. It can also make it possible to lift a crop such as carrots when harvesting would otherwise be virtually impossible. The equipment can also be used to guard against frost. These factors, together with timely marketing, have made irrigation an almost integral part of successful market gardening in this country. So much so, in fact, as to make almost superfluous any discussion of whether irrigation pays in this sphere.

The dairy farmer has the assurance that grass will be available throughout the summer; this makes increased stocking rates safe. The added skill required for irrigation is compensated by a reduction in the disturbances to the farm economy arising from variations in the amount of grass available.

The farmer gets the benefit not only of a higher but also of a more certain income; this is valuable for farm planning, for private budgeting and giving a feeling of security.

7.2 EFFECTS ON FARM MANAGEMENT

7.2.1 *General*

The introduction of irrigation may necessitate, or at least make desirable, various changes in the farm economy and these can be extensive. For example it is clearly advantageous for any farmer to increase the acreage of the crops which pay best. The extent to which it is possible to do this may be limited by several factors, such as the water supply, considerations of good husbandry (e.g. potatoes must not be grown too frequently on the same land owing to the risk

of eelworm), and labour availability. Further, the effect of higher yields and more intensive cropping on labour requirements can be considerable.

Where supplies of water are a restricting factor, it may be worthwhile to have two separate rotations on the farm: one near the water source incorporating the maximum feasible acreage of potatoes or vegetables, and the other away from the water source without these crops. In this way pumping, pipeline and labour costs are minimized. With grassland irrigation it may pay to concentrate irrigation in an area either near the water source, or near the farm buildings. Irrigation may also make more profitable rotations possible. Thus the root or ley break on farms primarily devoted to cereals, may be replaced by crops such as peas for freezing or canning.

7.2.2 Grassland

The main economic effect of grassland irrigation is to allow an increase in milk output per acre, chiefly by more intensive stocking; there may also be some saving in the use of concentrates. Higher output per acre may be achieved in one or both of two ways, by increasing herd size or by reducing the acreage of grass. If the herd is enlarged, the profitability of the irrigation depends on whether there is need for additional expenditure on labour, buildings and equipment. Similarly, if the grass acreage is reduced, the returns from irrigation are dependent on the profitability of the substituted crops. Assuming that irrigation is being used to allow an increase in herd size, an additional 80 to 100 gallons of milk per acre must be produced to cover irrigation costs of between £9 and £12 per acre. If a farmer retains the same number of cows on a reduced grass acreage, he may then need extra machinery and buildings to deal with the increased arable acreage.

Since meat production from grassland is generally less profitable than milk production, irrigation for beef and lamb enterprises is likely to show a correspondingly smaller economic advantage. No experimental evidence is available, but from calculations it would seem unlikely that irrigation for grass-fed beef can be profitable unless irrigation costs are abnormally low, and the grass and grazing management are of the very highest order. There may be circumstances where irrigation enables animals to be marketed finished, rather than as stores and in such special cases irrigation could be profitable.

The use of irrigation for intensive fat lamb production is probably more easily justified, though there is no experimental evidence available either on its effect on meat output or on such problems as parasitic larval populations. If early lamb production is being practised, the majority of the lambs may be going off the farm before irrigation gives its greatest effect. Where lambing takes place later, perhaps in March, the use of irrigation could be of greater benefit. In most circumstances an additional one-and-a-half lambs per acre would have to be reared and fattened before irrigation costs were covered.

7.3 BROADER ASPECTS

Apart from the effect on individual farmers, farming in general will be affected by the spread of irrigation. Much depends on how rapidly this spread occurs, and this will largely be determined by the availability of water (Section 8). Clearly, if irrigation spreads slowly, the effect on supplies, costs and prices will be concealed by other influences, particularly the extent to which other scientific advances occur.

Basically, irrigation, like other technical improvements, reduces unit costs of production—a primary aim in any industry. The farmers who irrigate benefit from increased profits, consumers may benefit from reduced prices, and the taxpayer may benefit from reduced subsidies. Farmers who do not irrigate are bound to suffer to some extent, assuming other circumstances remain the same. But irrigation is no different in this respect from other scientific advances. Progressive farmers will always benefit at the cost of those who lag behind, but not all farmers can take advantage of the possibilities offered by irrigation due to a lack of water supply, and those who can obtain water may have to expend widely varying sums to “harness” it. In the long run “irrigation potential” will have a marked effect on the relative prices and rental values of farms.

If irrigation spreads rapidly problems are bound to arise in the transition period, because the reduction in unit costs is associated with increased output. A large unsatisfied home demand (given a slightly lower price) may exist for certain products, e.g. certain vegetables, especially those which lend themselves to prepacking and freezing, fruits and meat, but for others the demand is already close to saturation point, e.g. potatoes and liquid milk. A marked increase in supplies of the latter is likely to cause a substantial drop in price. The country's population is increasing too slowly to make a noticeable increase in the demand for food over the next twenty years. Loss of agricultural land for urban development and other non-farm purposes, at present 0·1 per cent per year, is very small compared with the present rate of advance of agricultural output of 3 per cent per year. Furthermore, the demand for many agricultural products is not likely to increase very much even if the standard of living rises substantially during the next decade. For commodities such as potatoes, in fact, the total demand may well fall. Thus, irrigation is likely to have the effect of supplying a similar quantity of crops such as potatoes for smaller acreages, and of satisfying an increased demand—at lower average prices—for such products as fruit and vegetables.

Another possible beneficial effect of widespread irrigation is the stabilisation of prices. Not only will the fluctuation in yields per acre be less but the variations in acreage, induced by the consequent wide fluctuations in price, should also be reduced considerably. A relatively steady supply should give the consumer a far more stable price. A little more may have to be paid in wet years when, previously, a high yield often coincided with a large acreage, causing a glut which depressed prices, but this should be more than compensated by the absence of occasional very high prices resulting from a combination of low yield and reduced acreage.

Irrigation, by reducing unit costs, should also help our farmers to compete with foreign suppliers. With the setting up of the Free Trade Area and the possibility of our joining the Common Market this aspect is becoming particularly important.

SECTION 8

THE DEMAND FOR WATER

8.1 GENERAL

The potential demands for water for irrigation, present and future, are much less easy to determine than the demands for domestic and industrial use. This is mainly because irrigation on the present scale is a recent development. Future demand, especially in the long term, has to be judged more by the prospect of further development than on the rates of past increase, and the factors likely to influence future development can only be stated qualitatively, the past rate of increase giving no more than a general indication of likely development in the near future.

8.2 PRESENT DEMANDS AND RATES OF INCREASE

The principal work on the subject has been done by the Ministry of Agriculture which has provided, and is providing, approximate estimates for the use of the Ministry of Housing and Local Government, both for the Sub-Committee on the Growing Demand for Water of the Central Advisory Water Committee, and for the Surface Water Survey to use in its hydrological surveys of river basins^(8.1,8.2).

The Ministry of Agriculture estimates of present demand and rate of increase include figures for England and Wales as a whole, based upon information about such permanent installations as are grant-aided plus an allowance for purely portable systems. Approximately 130 000 acres are equipped for irrigation, and the rate of increase is about 15 000 acres per annum.* These estimates have been found to correspond reasonably well with information supplied in confidence by irrigation equipment manufacturers.

Estimates of present demand† and rate of increase in the next few years have also been produced for the Great Ouse, Severn, Essex and Wear and Tees hydro-metric areas, based on information from various sources, including statistics of permanent installations which have been grant-aided, the National Agricultural Advisory Service, and River Boards (Table 8.1). What proportion recorded installations represent of the whole is unknown, but before 1959 it was probably substantial. However, a large number of portable installations were sold during the dry summer of that year, and information about these is not readily available.

*With a seasonal requirement of 4 inches, about 12 000 million gallons of water are required for 130 000 acres in a dry season; if the maximum overall daily application rate is $\frac{1}{16}$ inch, the peak daily demand is 200 million gallons per day, if $\frac{1}{12}$ inch it is 300 million gallons per day.

†The total amount of water applied is also uncertain. In an investigation^(8.3) into irrigation on 12 farms for the Agricultural Improvement Council during the three years, 1956-8, the average amounts of irrigation applied were 3.3 inches, 3.3 inches and 1 inch respectively; 1956 and 1957 were years of moderate need and 1958 was very wet. A survey was carried out in the very dry year 1959 of 166 farms in most of the counties of the South, East and Midlands, with a preponderance in East Anglia, and showed that the average application to grass, potatoes and sugar beet was about 3.5 inches, the amount varying from under 1 inch to over 10 inches.

TABLE 8.1

Estimates of present irrigation development and increases in the next 10 years
(Ministry of Agriculture)

Hydrometric area	Known Development (a)					Future Development (c)		
	Maximum seasonal requirement -inches	Installations	Estimated area (b) -acres	Maximum requirement million gallons		Estimated annual increase		Maximum requirement -million gallons
				Daily (d)	Seasonal (e)	Area -acres	Daily (d)	
River Great Ouse ..	8	380	17 000	26	3 000	2 600	3.9	460
River Severn ..	6	380	8 600	13	1 200	970	1.5	130
Rivers Wear and Tees	5	22	375	0.57	45	100	0.15	11
Essex Rivers ..	9	180	7 100	11	1 400	560	0.84	120

Notes

(a) Known development

(b) Estimated area

(c) Future development

(d) Maximum daily requirement

(e) Maximum seasonal requirement

Refers to those installations which happen to be known to the Ministry of Agriculture.
An estimated acreage which includes an allowance for the known installations for which no acreage data are available.

Based upon the personal opinion of local officers.
Allowed at $\frac{1}{12}$ inches per day.

Based on driest year in ten, potential transpiration and an allowable water deficit of three inches.

8.3 THEORETICAL LIMIT OF DEVELOPMENT

In addition, the Ministry of Agriculture has made estimates of the theoretical limit of development. These were made to set a ceiling to potential irrigation development at a time when the factors controlling this development were even less certain than now. These estimates were never intended to be regarded as giving any indication of likely development but only as a first attempt to assess the acreage potentially irrigable. The acreages of different crops in 15 hydrometric areas (corresponding roughly to that part of the country where there is a theoretical irrigation need more than 5 years in 10) have been calculated. The crops have then been grouped in order of likely irrigation priority as judged by their economic response. The water requirements have been calculated for each year to a standard pattern of variation for a ten-year period, and the potential water demand for the driest year has been given together with the estimated peak daily demand. The values for the Great Ouse, Severn and Essex Rivers hydrometric areas are given in Table 8.2.

TABLE 8.2
Theoretical limit of irrigation development
(Ministry of Agriculture)

Hydrometric Area	Irrigated area— (thousand acres)	Maximum requirements— (thousand million gallons)	
		Daily	Annual
River Great Ouse	840	1.3	150
River Severn ..	1 600	2.4	220
Essex Rivers ..	350	0.5	71

Maximum seasonal requirements are based on driest year in 10, potential transpiration and an allowable water deficit of 3 inches.

8.4 PRACTICAL LIMIT OF DEVELOPMENT

Clearly, for economic reasons, the theoretical limit of development, which is based on satisfying the water requirements of all crops in full, even in the driest years, will not be attained in practice. This report attempts to make estimates of the practical limit of development. The modifying factors fall into two groups, those which affect the areas irrigated and those which concern the volume of irrigation water to be applied. The broad assumptions made are as follows:

- (1) There will be little change in the general pattern of farming in this country as a whole.
- (2) It will never be economic to provide water in quantities sufficient to meet the total demand in the driest years in the driest areas; the present estimates are intended to meet the demand substantially in all except the two driest years out of ten in the south and east and all except the driest year in the north and west. This is called the economic peak seasonal requirement.

(3) It is most unlikely that the whole area even of responsive crops will be irrigated, except for certain horticultural crops. The estimates of the actual areas that are likely to be irrigated are set out in Appendix B. For potatoes and sugar beet some reduction has been made in total area to allow for increased yields in the irrigated area.

(4) Some small growers or farmers are unlikely to use irrigation with many crops because of the labour demand, whereas large holdings may irrigate crops other than those listed below. Differences are assumed to cancel out in terms of total water requirements, except for potatoes and sugar beet.

(5) It will be possible to provide water at low cost.

Estimates on these lines have been made for England and Wales as a whole, and for two of the hydrometric areas for which the Ministry of Agriculture has already given the theoretical limits, viz., the Great Ouse and Severn.

8.4.1 *Method of calculation; England and Wales*

Where the average rainfall exceeds 35 inches it is unlikely that irrigation of most crops will be economic. Detailed examination of the country on this basis has not been carried out, but practically the whole of Wales (excepting Pembrokeshire which has dry springs and where early potatoes are grown) and the counties of Cumberland, Durham, Northumberland, Westmorland, Lancashire and Yorkshire (North and West Ridings) have an average rainfall in excess of 35 inches; the acreages of crops grown in these counties have therefore been excluded. Although some parts of these counties and of Wales* receive less rainfall, these will be balances against small areas of high rainfall and high elevations elsewhere.

In the south and east the estimates of the maximum annual requirements are based on the provision of sufficient water to meet the calculated deficit substantially, though not entirely, in about eight years in ten. This provision ranges from about 3 inches for the counties near the "border" (e.g. East Riding, Warwick and Wiltshire) to 5 inches for the more arid counties (Suffolk, Essex and Kent); a general value is about 4 inches (except for early potatoes which have a short season and normally require 2 inches). In the north and west the general value is 2 inches but where the frequency of irrigation need is less, it is desirable, if irrigation is to be worthwhile, to meet demands even in the driest years of an average ten-year period. The requirement on this basis is also about 4 inches but in a ten-year period this amount will be required less often than in the south and east.

The likely maximum annual demand for water for England and Wales in a ten-year period, assuming an application rate of 4 inches in the season for all crops except early potatoes, is given in Table 8.3. This method of computation gives what is essentially an aggregate of the maximum annual demands for the different parts of the country. Since years which are dry in one part are sometimes average or even wet in another, the true maximum demand for the whole country on the given premises will be less than the maximum shown. In the absence of any large-scale system for the transfer of water from one part of the

*This statement has been confirmed for Wales by the report of the Welsh Advisory Committee (1944). The report suggests that although irrigation is valuable in some parts of Wales, the total demand is unlikely to exceed 80 million gallons per day; by the methods given in this section their total is likely to be an over-estimate.

TABLE 8.3
Practical limit of irrigation development for England and Wales

Crop	Area under crop, 1959 (thousand acres)			Fraction to be irrigated -per cent	Estimated irrigable area (thousand acres)			Maximum annual demand (thousand million gallons)		
	SE	NW	Whole		SE	NW	Whole	SE	NW	Whole
Early Potatoes ..	60	35	95	80	48	28	76	2.2	1.3	3.5
Maincrop Potatoes ..	280	190	470*	48	140	92	230	13	8.3	21
Sugar Beet ..	350	67	420	44	160	29	190	14	2.7	17
Grassland ..	6 800	6 400	13 000	5.7	380	370	750	34	33	67
Vegetables ..	300	120	420	35	110	42	150	10	3.8	14
Tree Fruit ..	180	60	240	20	36	12	48	3.2	1.1	4.3
Small Fruit ..	30	3	33	40	12	1.2	13	1.1	0.1	1.2
TOTAL ..	8 000	6 800	15 000	10	890	570	1 500	78	50	130

*This figure fluctuates considerably and the acreage may well be 20 per cent higher.

country to another the maximum shown is the relevant figure, and gives the total provision that will have to be made for water supplies to provide for irrigation on the scale envisaged.

The variation in peak daily demand through the season based on an application rate of 1 inch every 10 days through the season is given in Table 8.4. With some crops, notably grass, there is a long growing season and the crop can usefully be irrigated through that period; with others, e.g. early potatoes, the season is much shorter.

TABLE 8.4
Size and duration of economic peak daily demands
(millions of gallons per day)
(drought periods)

Crop	April	May	June	July	August	September
Early Potatoes ..		170				
Maincrop Potatoes			520			
Grassland ..	1700					
Sugar Beet ..			430			
Vegetables ..	340					
Tree Fruit ..		110				
Small Fruit ..		30				
TOTAL ..	2000	2400	3100	2600	2100	

8.4.2 Method of calculation; hydrometric areas

Similar estimates can be made for hydrometric areas. For accurate estimates on rainfall, potential transpiration, soil type and crops grown in the areas, more detailed information than is available is required. Soil texture influences the kind of crops which can be grown, the amount of water available and its release to plant roots; this is especially important with quick-growing comparatively shallow-rooted vegetables, which have a high demand for water. So far the moisture characteristics of only a few soils have been studied, but extension of such knowledge should enable water supplies to be allocated to those sites and crops where they will have the greatest effect. For grass, however, experimental work so far indicates that soil type is unlikely materially to influence the area

irrigated and hence differences in soil type can be ignored. With only a small area, e.g. a farm, it is possible to inspect all fields, and, providing there is no major change in farming policy, produce a fairly accurate estimate of irrigation requirements. On the larger scale of a hydrometric area, this is not at present possible, and a similar approach to the one used to estimate the irrigation demand for the country as a whole has to be employed.

Estimates for two hydrometric areas and their sub-divisions have been prepared, one for the River Ouse (Table 8.5) and the other for the River Severn (Table 8.6). One-third of the vegetable acreage, one-third of the irrigable farm crop acreage, and half an acre of grassland per dairy cow is assumed to be irrigated. The estimated rainfall totals and potential transpiration figures for each group of crops have been compared and the probable solid moisture deficit year by year over a ten-year period has been calculated for each sub-division.

The estimates of peak daily demand provide for 1 inch of water per acre in 10 days over the whole of the irrigated area; this should meet peak demand during June, July and August, which are the most important months for crop growth. The estimates of maximum seasonal demand are also made on the basis of meeting the deficit substantially, but not entirely, in 8 years out of 10 in the Great Ouse area, and rather more completely in the River Severn area where the demand is likely to be less frequent.

8.5 DISCUSSION

All the estimates are very rough but they provide some indication of the likely practical limit of development. They are far below the corresponding development limits estimated by the Ministry of Agriculture for the Surface Water Survey (Table 8.2). The Ministry of Agriculture have always made it clear that the latter estimates, based on irrigating to the full the total acreage of all crops likely to benefit, are merely ceiling figures and in no sense represent the development to be expected. The modifying factors introduced for the acreages and amount of irrigation required radically reduce the ceiling estimates, most of the reduction being due to using the number of dairy cattle, instead of the total grass acreage, as a basis for estimating the development of irrigation on grassland. Moreover, the present estimates assume that water can be provided at low cost. If the cost of water rises substantially, considerable further reductions will be made in the maximum annual demands for grass, which constitute about 50 per cent, 30 per cent and 67 per cent of the total estimated annual demand for England and Wales, the Great Ouse and the Severn respectively; the irrigation of grass is only likely to be profitable where the cost of water is low (see Section 7, page 55).

Comparisons of present demands with the practical limit requirements can best be made on the basis of acreage, the water requirements being assumed proportional. In the River Great Ouse Basin for example, about 7000 acres are estimated to be irrigated at present (Table 8.1) compared with the practical limit of 130 000 acres (Table 8.4) which is about 18 times as great. In the Severn area the practical limit is about 13 times the present acreage. For England the practical limit of 1 500 000 acres is about 12 times the present acreage and about 10 per cent of the total acreage.

Even the present development of irrigation has led to a demand for water in certain areas which exceeds the supplies readily available⁽⁸⁻⁵⁾. Recently published

TABLE 8.5
River Great Ouse. Practical limit of demand. Probable number of years required 7-10 in 10

Sub-division of Hydrometric Area	Crop	Area irrigated (thousand acres)	Irrigation applied -inches	Total acre- inches applied (thousands)	Maximum annual demand (million gallons)	Peak daily demand (million gallons)
I	Vegetables ..	0.8	4	3.2	72	
	Farm Crops ..	1.3	4	5.2	120	
	Grass ..	9.5	5	48	1 100	
	Total ..	12	-	56	1 300	27
II	Vegetables ..	8.8	4	35	790	
	Farm Crops ..	8	4	32	720	
	Grass ..	5	6	30	680	
	Total ..	22	-	97	2 200	50
III	Vegetables ..	4.8	4	19	430	
	Farm Crops ..	27	4	110	2 500	
	Grass ..	3	6	18	410	
	Total ..	35	-	150	3 300	79
IV	Vegetables ..	7.8	4	31	700	
	Farm Crops ..	33	5	165	3 700	
	Grass ..	10	6	60	1 400	
	Total ..	51	-	260	5 800	120
V	Vegetables ..	2.5	4	10	230	
	Farm Crops ..	5	5	25	570	
	Grass ..	3	7	21	470	
	Total ..	11	-	56	1 300	25
Hydrometric Area	Vegetables ..	25	-	-	2 200	-
	Farm Crops ..	74	-	-	7 600	-
	Grass ..	31	-	-	4 100	-
	Total ..	130	-	-	14 000	300

TABLE 8.6
River Severn. Practical limit of demand. Probable number of years required 5—7 in 10

Sub-division of Hydrometric Area	Crop	Area irrigated (thousand acres)	Irrigation applied —inches	Total acre-inches applied (thousand)	Maximum annual demand (million gallons)	Peak daily demand (million gallons)
I	Vegetables ..	0.015	4	0.06	1	
	Farm Crops ..	0.5	3	1.5	30	
	Grass ..	6	4	24	540	
	Total ..	6.5	—	26	580	15
II	Vegetables ..	0.6	4	2.4	50	
	Farm Crops ..	9.3	4	37	840	
	Grass ..	23	5	120	2 500	
	Total ..	33	—	160	3 400	75
III	Vegetables ..	2	4	8	180	
	Farm Crops ..	12	4	48	1 100	
	Grass ..	7.5	6	45	1 000	
	Total ..	22	—	100	2 300	50
IV	Vegetables ..	6	4	24	540	
	Farm Crops ..	7	4	28	630	
	Grass ..	14	6	84	1 900	
	Total ..	27	—	140	3 100	61
V	Vegetables ..	0.4	4	1.6	40	
	Farm Crops ..	5.3	4	21	480	
	Grass ..	19	5	95	2 100	
	Total ..	25	—	120	2 600	57
Hydrometric Area	Vegetables ..	9.0	—	—	800	
	Farm Crops ..	34	—	—	3 100	
	Grass ..	60	—	—	8 000	
	Total ..	110	—	—	12 000	260

hydrological surveys^(8.1, 8.2) suggest that in the River Great Ouse, existing supplies are sufficient only for a limited expansion of irrigation and no water appears to be available for irrigation purposes in the Essex Rivers and Stour^(8.6) although a much larger expansion could be permitted in certain areas of the River Severn without special conservation measures.

Methods of allocating water will be influenced by many factors. Obviously public supplies for domestic purposes must take priority but the methods of allocating water for other purposes, including water produced by conservation measures, cover a wide range of possibilities. It is understood that some consideration has already been given to this subject by the Ministries concerned. The technical, legal and administrative problems require special study and the most careful consideration if equitable arrangements are to be made. Irrigation in any area can only develop if assured of a sufficient, reliable and continuous supply of water to justify outlay and re-organisation needed on the farm. This will require planning within hydrometric areas, and where practicable, between them.

For the immediate future, to ensure that the water resources of each region are most profitably employed, studies similar to that at present being undertaken by a working party on the future development of water resources of the River Severn are necessary. Water conservation authorities should have this aspect much in mind; because of the interest of the users and the complex nature of their demands, any such water conservation authority should have users of irrigation represented upon it.

REFERENCES

- 8.1 HYDROLOGICAL SURVEY, 1960. River Great Ouse Basin, Ministry of Housing and Local Government, H.M.S.O., London.
- 8.2 *Ibid.* River Severn Basin.
- 8.3 Agricultural Improvement Council Land Management Committee. Irrigation Investigation (unpublished information).
- 8.4 Welsh Advisory Water Committee (1961). *Report on the Water Resources of Wales* (Cmd 1331). H.M.S.O. London.
- 8.5 Central Advisory Water Committee (1960). *Sub-Committee on the Growing Demand for Water: Second Report*: (S.O. 75-9999. H.M.S.O., London).
- 8.6 HYDROLOGICAL SURVEY, 1961. Essex Rivers and Stour. Ministry of Housing and Local Government, H.M.S.O., London.

SECTION 9

PROBLEMS FOR FURTHER STUDY

9.1 GENERAL

Irrigation research in this country has already shown the value of irrigation to the farmer and community, but more research is necessary to establish in detail results, costs and returns of irrigation applied to various crops under various conditions, and the consequent potential demand for water and its distribution and magnitude. The most urgent need is for research directed to enable the limited supplies of available water to be utilized most effectively and profitably. Because one limiting factor in irrigation is shortage of water, research should also be directed towards reducing the need for artificial water. Practicable methods (e.g. by mulching) are required for reducing the considerable losses by evaporation from bare soil. Quantitative forecasting of rainfall for periods of days ahead would ease planning of water supplies and reduce wastage of water by premature irrigation.

Such information is already available on the meteorological aspects of irrigation and farmers who irrigate or intend to irrigate can now find out, either through their local N.A.A.S. officers or from the Meteorological Office direct, what the transpiration of the previous month has been and hence with their own rain gauge they can estimate the current soil moisture deficit. Such information that is available needs to be brought more positively to the attention of the users.

9.2 PROVISION OF WATER

The problems of the provision of large quantities of water for irrigation range from purely administrative to purely technical. The problems of organization, co-ordination and control which arise have to be considered in the general context of water supplies and conservation at national regional (hydrometric area) and local levels.* As irrigation develops, more detailed and accurate estimates of the future demand for water will be needed.

The merits of large reservoirs that require distribution systems need to be compared with those of small reservoirs adjoining the land to be irrigated. The possibilities of artificial recharge of aquifers and of demineralization processes also require examination. Water quality is also important; existing information on the salt and pollution tolerance of crops needs to be collated and where necessary extended.

Storage on the farm is the only conservation action taken so far to provide water for irrigation and may prove to be the most practicable method of water provision in the future. As more reservoirs are constructed, the need to ensure their safe and economic planning and execution will increase.

Each reservoir presents a special design problem, and should be considered as part of a co-ordinated plan for the river catchment or other hydrometric area.

*The Sub-Committee on the Growing Demand for Water of the Central Advisory Water Committee of the Ministry of Housing and Local Government is at present reviewing this subject.

Such problems are capable of solution by the application of known techniques, and engineering advice is needed rather than new research.

There is scope for applying analytical techniques, notably soil mechanics, to the design of earthworks. This has not yet been applied to the comparatively minor engineering works considered here, but may have some part to play in a simplified form.

While the need for proper survey, design and constructional methods is fully appreciated for large public water works, the similar needs of small farm reservoirs are only now beginning to be recognized; the cost of the proper design and supervision may be a considerable proportion of the total cost. Most farm storage schemes are grant-aided and, in order to obtain grants, details of the proposals have to be submitted to the Ministry of Agriculture, Fisheries and Food. These proposals are usually considered by the Ministry's Regional Engineers, but these officers are not at present permitted to give advice to farmers, a ruling that might well be reconsidered. The Land Drainage and Water Supply Division of the Ministry of Agriculture, Fisheries and Food is at present considering various aspects of reservoir design, and is preparing drawings in an attempt to indicate general standards and methods of approach. Further consideration should be given to the possibility of constructing demonstration reservoirs under differing conditions to test the applicability of design and constructional methods.

Whilst professional advice can already do much for the successful development of small reservoirs, there are some problems peculiar to small reservoirs which merit further study, these include:

- Measurement of discharges from small catchments
- Desirable standards for site investigation
- Earthworks standards
- Inlet, outlet and overflow works
- The need for lining
- Methods of lining.

Some of these problems are at present being investigated; e.g. the run-off from a small catchment area in the Thames Valley is being measured, but such studies, in less detail, may be necessary over other catchment areas.

9.3 CROP RESPONSES AND THE EFFICIENT UTILIZATION OF WATER

The response of crops to a given volume of irrigation water depends upon a number of factors including the type of crop, the stage of growth at which water is applied, the current soil moisture deficit, soil texture and structure, and general growing conditions. Further research is required on all of these.

Probably the most important in the long term is to determine the maximum deficit which each crop can tolerate at each stage of its growth without seriously impairing the yield or quality of produce. To make the best use of limited amounts of water it is desirable to know at which stages of growth the various crops are most sensitive to water shortages. Interactions between water supply, plant spacing and level of nutrition also need to be elucidated.

There are a number of basic problems related to plant growth which are relevant to investigations on the effects of irrigation. The principal ones are:

- The extent and functioning of plant root systems and the way in which these are affected by water and nutrient supplies and cultural practices:
- The effect of various soil factors such as physical structure and organic

matter on water retention, and water availability in particular, on field capacity, permanent wilting point and the tensions at which water is held at different degrees of soil drying.

9.4 GRASSLAND PROBLEMS

More information is required on the behaviour of different species of grasses and legumes, and mixtures of them, under irrigated conditions. Nutritive value and palatability as well as yield must be studied, as well as the best use of fertilizers and possible changes in rotations. Profitable exploitation will usually mean increasing the stocking rate to utilize the extra herbage. The methods of husbandry adopted to utilise the extra and more regular production require exploration both for dairy stock and for other types of livestock; otherwise the combination of manuring, heavier stocking and irrigation may increase risks from disease, such as footrot, metabolic upsets (bloat, scouring) and internal parasites.

9.5 ECONOMICS

The effects of the contribution of irrigation to the lowering of unit costs of production of various crops needs to be determined more accurately, in order to find which need to be given priority when water is limited. Since the need for irrigation varies from year to year, the effect this has on costs and profits in different parts of the country requires study. The effect of introducing irrigation on the farm economy as a whole needs more study. Surveys of existing irrigation practice in different areas and under different conditions are required.

9.6 APPLICATION OF WATER

There are several outstanding problems in irrigation techniques; one of the most important is to determine the maximum rate of application and the quantity of water that may safely be applied at different stages of crop growth. Too high a rate of application is known to damage soil structure and also the crop but the critical rates have not been determined accurately for different soils.

More work is required on the design of irrigation equipment to improve the efficiency of application, including the uniformity with which water can be sprayed, and the size of nozzles and jets needed to bring the droplet sizes within the range least likely to cause damage to the soil and crop. Special nozzles are needed to given even spreading of water for frost protection. The use of impure and polluted water may cause damage to soil structure, and is likely to have an even more serious effect on public and animal health. Further study in the field might increase the efficiency of handling irrigation equipment.

9.7 ORGANIZATION OF RESEARCH AND DEVELOPMENT

The problems outlined above range over soil chemistry and physics, engineering, studies of equipment and of water conservation, plant breeding and physiology, plant diseases and pests, crop and animal husbandry and economics. An analysis of research problems giving priorities is attempted in Appendix C. Their solution demands different approaches; some call for fundamental research.

Because of the wide variety of problems and the number of research organisations, ranging on the agricultural side from the universities to experimental husbandry farms, consideration should be given to setting up a Committee

under the Agricultural Improvement Council or the Agricultural Research Council to review developments and to make recommendations both for research needed and its dissemination.

Some of the N.A.A.S. Experimental Horticulture Stations and Experimental Husbandry Farms have irrigation equipment and technical staffs trained in irrigation experimentation. Such facilities should be made available to all suitably-sited N.A.A.S. Stations, and more use should be made of them by irrigation research workers.

It may well be that the problems are numerous and important enough to justify establishing an Irrigation Area or Areas with an Irrigation Research Station or a Ministry of Agriculture Husbandry Farm within it. The primary aim would be to investigate and demonstrate the effects and consequences of irrigation both in relation to crops and farming systems. The Irrigation Research Station or Husbandry Farm would be the means of extending small scale experiments in the laboratory, or on the research station, to field and farm scale. It would also provide a means of integrating all the advisory aspects of irrigation, from changes in the management of crops to the building of reservoirs. Such an area or areas would enable the financial and engineering aspects of the provision of water over an area to be assessed.

SECTION 10

SUMMARY AND RECOMMENDATIONS

10.1 IRRIGATION NEED

Research and practical experience have shown that many agricultural crops only attain their maximum growth and yield under conditions of plentiful water supply. In many parts of Britain shortage of rainfall in the six summer months leads to considerable reductions in yields of some crops, and to large variations in yield from year to year. If the water shortage is made good by irrigation, average yields are increased and the year-to-year variation in yield is lessened.

The extent and frequency of irrigation need can now be specified with fair precision. The amount of water that crops use when there is sufficient water available at their roots to meet current requirements has been estimated from physical reasoning and experimental evidence. The quantity needed varies slightly from year to year, and a little more markedly from region to region, but these variations are much smaller than the yearly and regional variations in summer rainfall. Detailed study of climatic records, region by region, has shown how summer rainfall compares with water requirements, and, after making an allowance for stored water in the soil, the data can be presented as a map of frequency of irrigation need (Fig. 1). The map almost certainly under-estimates the frequency with which grass, vegetables and potatoes respond to irrigation, is about right for beans and fruit, but over-estimates the need for sugar beet and cereals; these conclusions are based on experiments at research stations and are supported, qualitatively at least, by available farming experience. Broadly, for optimum growth, there is need for irrigation in some part of the season in more than five years out of ten in the area south-east of a line from about Hull to Torquay, with an outlier in the lee of the Welsh mountains; and the need increases to nine years out of ten around the Thames estuary. Two characteristics of the drier areas are noteworthy, and relevant. First, the most needy areas are those that already experience occasional water shortages affecting the whole community. Second, many farmers in the area have already found out that irrigation is profitable.

As the value of irrigation has become more evident, and as more information has become available from research and experiment, more and more farmers have installed irrigation equipment; and irrigation has been increasingly applied not only to market gardens, which led the way, but also to fruit, potatoes, sugar beet, grass and other crops.

There is still much to be learned about irrigation management. To convert "frequency of need" to "frequency of benefit" the correct amount of water must be applied at the right time. But already several techniques and devices are available for helping a farmer to decide how much water to apply, and the risk of wasteful application can be almost completely eliminated.

10.2 METHODS

There are three main techniques, only one of which, overhead irrigation, is important in this country. In a few areas, e.g. the Fens, sub-surface irrigation

may be possible by water-table management; and there are a few places where surface irrigation could be employed, but this form of irrigation wastes water and cannot be recommended. In the third technique water is applied through spray lines or from rotary distributors. Spray-lines and the smaller rotary sprinklers give low rates of irrigation and are usually safe on most soils. The large ranguns may damage bare soil or young plants, but they are successfully used where the soil has good cover from an established crop such as sugar beet or grass.

Physical and financial circumstances on individual farms influence choice of equipment and affect installation and running costs. Sometimes, everything may be permanently installed—pump, mains and sprinklers—but though running costs for labour are small the capital cost is high, even after allowing for possible Ministry of Agriculture grants. The next form, more common, is part-permanent, with permanent distribution mains (buried) and moveable sprinklers. Portable systems have everything moveable and enable an area many times greater than that covered by one setting of the equipment to be irrigated.

10.3 SOURCES OF WATER

To obtain water for irrigation farmers have had recourse to a variety of sources of supply, sometimes—and now increasingly—in competition with other users. Broadly, supplies for all purposes come either by abstraction from surface flows, or from ground water. The abstraction of ground water is controlled by Act of Parliament and future control of surface flows has been recommended. Public supplies have priority, and they have the great engineering asset of their demand remaining relatively constant from day to day, and from year to year. The irrigation requirement is always a summer requirement, with the peak load on average in mid June or early July, but it can occur in May, June, July or August. Inevitably these peak requirements occur when surface flows are at or near their minimum and when underground stores are decreasing, and almost inevitably coincide with an increased demand from other users.

So far the main expansion of farm irrigation has been based on direct abstraction from streams and rivers. It is popular because it is cheap, but there are obvious limits to what can be taken from streams in dry weather and some River Boards consider that the limit has been reached. Many farmers use ground water from wells and boreholes, particularly in south-east England, but here too, the limit may soon be reached. Occasionally, there is use of a public mains supply, but as this is expensive it is chiefly used in market gardens of small area for which returns are high. Local storage in farm reservoirs is increasing and is often the only practical solution. The Ministry of Agriculture makes a grant to aid the building of such reservoirs, and about 250 grants have been made since 1956.

The main prospect for substantial expansion of irrigation in the areas where it is of most value lies in increased conservation of water. Under present conditions local storage is the most promising method, but regulating and other types of large reservoirs, including reservoirs primarily designed for regulating the flow of rivers, may need to be considered. Ground water storage may also be augmented by artificial recharge of aquifers. All forms of conservation works need co-ordination to be fully effective and to bring about the most efficient development of water resources.

10.4 COSTS

Two sample surveys showed a very large range in the amounts that farmers had spent on equipment, and considerable variation in running costs. The initial capital cost may include the sinking of a borehole, building a reservoir, laying a permanent main from a river, a pump, delivery lines and sprinklers. With "free" water, capital costs average about £25 per acre, on which annual depreciation and interest amount to about 25s. 0d. per acre-inch with a standard application of 3 inches. The capital cost may be more than doubled if a borehole or reservoir is required. Running costs, consisting primarily of labour and pumping, average approximately 20s. per acre-inch. Total costs therefore average about 45s. 0d. per acre-inch or £6 per acre, with "free" water. If water has to be bought from a public supply the cost is increased by about 60s. 0d. per acre-inch, with water at 2s. 6d. per 1000 gallons.

10.5 RESPONSE OF CROPS

Irrigation cannot work agricultural miracles and is no more than an assistance to good husbandry. Other things being equal, the growth of an irrigated crop is the same as that of a similar crop grown with sufficient summer rainfall, and a large response to irrigation is a measure of the poor yield of the non-irrigated crop.

The main direct effect of irrigation is to encourage leaf growth (hence its value for grass); because the growth of other parts of a plant is not always correspondingly large, the response in terms of the saleable product varies greatly with plant type. Broadly, however, the meteorological frequency of need (Fig. 1) is a very good estimate of the farming frequency of benefit averaged over grassland and the crops of normal arable rotations.

For grass, the response varies greatly with type of mixture and management, but in the years that irrigation is needed the increased yield is of the order of 4 cwt dry matter per acre-inch of irrigation. The long-period average response is smaller, because a watering is "wasted" when it is done in ignorance of the imminence of a spell of wet weather. Not the least important aspect of irrigated grass is its continuity of growth, an asset in feeding a herd of cattle or keeping grass-drying equipment in continuous operation.

Potatoes share with grass a susceptibility to small soil moisture deficits, so that they too respond to irrigation more often than the frequency map suggests. The order of response is 1.5 tons for early and 1 ton for maincrop potatoes per acre-inch of irrigation, and a few inches of irrigation on part of present potato acreage could eliminate the major fluctuations in annual yields. Sugar beet is a crop that gives spectacular returns in drought years, but, being a deep-rooting crop, it is not so susceptible to water shortages in most summers. Over the period 1948-49 the average response to the best treatments in experiments was 2½ cwt sugar per acre-inch of irrigation. A little more experience in management is needed before this becomes a routine response, possibly when better plant hygiene is generally achieved. Sugar beet tops, a valuable by-product, respond a little better than roots.

Spring cereals respond to irrigation only when May and June are very dry, giving in one experiment about 2 cwt grain per acre-inch. Nevertheless, a cereal will usually be a part of a sequence of cropping and, if the irrigation equipment is not in use elsewhere a spring watering may be profitable.

Of other crops, field beans may well become an economic crop in south-east England if they can be irrigated; in dry summers the response is very great. Almost every vegetable crop is worth irrigating in a dry spell, either to increase crop yield, obtain an earlier crop or improve quality, but as some of these crops respond mainly at certain periods of their growth, care must be taken to irrigate them at the right time. Peas, cauliflowers, lettuce, cabbage, carrots, red beet, beans, turnips, radishes and celery all respond to timely irrigation, though experimental work has not yet reached the stage at which firm quantitative estimates of benefit can be made for all of them.

Fruit benefits also and, because irrigation affects the development of the bush or tree as well as the current year's crop, it has cumulative effects. In Kent, strawberries, raspberries and blackcurrants gave responses (averaged over two or more years) of about 3 to 8 cwt fruit per acre-inch of irrigation. Fruit trees do not need irrigation when grown on a deep soil that permits full root development, but many orchards are on soil little more than two feet deep and here good responses are obtained; the average response over six years in one apple experiment, for example, was 29 bushels of apples per acre-inch of irrigation, with more of the apples of the best selling size.

Further uses of irrigation equipment are to combat frost and to spread fertilizers. Irrigation *before* frosts can give limited protection to low-growing crops such as strawberries and potatoes; very effective protection can be given to tree fruit, bush fruit and some other crops by continuous sprinkling *during* frost, the water releasing latent heat as it freezes.

10.6 RETURNS

Gross responses and net returns from irrigation depend on a number of factors, including crop, soil, climatic conditions, water availability and cost.

Irrigation pays best for vegetables and fruit; indeed very few market gardeners can afford to be without it. Potatoes also give good returns and grass for intensive dairying, field beans, and sugar beet can all justify irrigation with water at low cost.

Because irrigation equipment can be used successively on different crops, the individual farmer has to work out his costs and expected returns from the farm as a whole. Thus, equipment otherwise idle may be used for spring cereals which give a relatively small return. Apart from increased yields, additional gains may be expected from many crops through better quality and more timely harvesting. Frozen food processors, when offering contracts, already tend to favour growers who use irrigation because of the certainty of production and the constancy of the flow of produce. Irrigation should make yields more reliable and will lead to modifications in the cropping and stocking of farms.

For the consumer there is the possibility of a more even flow of produce of better quality, with less variability in prices. This seems to be happening already with market garden crops, for in 1959, the driest summer for many decades, there were no "famine" prices. On the national scale the rapid expansion of irrigation could produce embarrassing surpluses of some products for which demand is inelastic. In time, however, free market forces should lead to reduction in the area under such crops, leaving more for those, such as fruit and vegetables, whose sale responds more favourably to a slight fall in price. Another

possibility is the concentration of the high-value crops on the soils and sites best suited to grow them, freeing other areas for crops not so dependent on water supply.

10.7 DEMAND FOR WATER

The present area irrigated, about 130 000 acres, may grow, at the present rate of expansion by approximately 15 000 acres per annum to about half a million acres by 1980, provided that water can be obtained at reasonable cost. The seasonal need in a dry year, calculated on the basis of a supply equivalent to 4 inches, would be about 50 000 million gallons and the way in which the need may vary within the season may be estimated from the calendar in Appendix A. This quantity should meet demands in the south and east in eight years out of ten, and in the north and west in about seven out of the eight years in which irrigation is needed; the less frequent the need, the greater the economic necessity to meet it in full to justify the purchase of equipment.

Estimates of the practical limit of demand, assuming no serious change in the pattern of agricultural production, have been made for England and Wales and for two hydrometric areas, the River Great Ouse and the River Severn, together with estimates of the peak daily demand. These estimates suggest that in England and Wales, the area irrigated, if water is available, may rise to about one million and a half acres with a peak annual demand of over 100 000 million gallons. Increased costs of source works and other charges for water supplies may reduce the ultimate demand but even so, the water likely to be required is substantially in excess of present-day demands and indeed present-day supplies. Fresh consideration of the general problem of water conservation and an increased effort on the part of the authorities is required in order to meet these demands.

10.8 RESEARCH PROBLEMS

The efficiency of irrigation, already high, can be raised and costs lowered provided some obvious problems are solved. Some are fundamental, concerned with understanding what is happening to a plant when it is short of water: some are technical, aimed at more skilful use of irrigation. They present challenges at all levels: to research scientists and experimental agronomists on the growth problems; to hydrologists, water engineers and meteorologists on the supply problems; and to economist and farmers in getting the best out of the water in crop and cash. Overlying all is the main problem: "Can the water be supplied?"

10.9 RECOMMENDATIONS

The benefits of judicious irrigation are such that every effort should be made to enable it to be widely extended. As a guide to present action the following recommendations are made:

RECOMMENDATIONS

1. Because of the benefits to users, consumers, and the nation, the judicious use of irrigation in agriculture and horticulture should be encouraged.

2. After domestic requirements have been satisfied, with provision for garden and amenity uses, the supply of water for agricultural irrigation should be considered together with that for industrial purposes. Horticulture should receive priority.

3. Increased conservation of water for irrigation should be encouraged, especially by local storage in small units close to the land to be irrigated. Conservation works should be properly planned in relation to each other, and in conjunction with the proper development of the water resources of the whole catchment or other hydrological area.

4. Farm reservoirs, as part of the efficient development of the water resources of an area, must be designed and constructed to high standards, ensuring safety and economy.

5. More research is needed:

- (a) Fundamental, on the water relations of crops, that is the inter-relationships between plants, soils and water.
- (b) Technical, on the responses of crops to irrigation and the management of irrigation equipment.
- (c) Operational, to obtain information on current practices. Questions on irrigation should be included in the Agricultural Returns of the Ministry of Agriculture, Fisheries and Food and surveys of irrigation practice should be undertaken.

Consideration should be given to establishing an Irrigation Area and within it an Irrigation Research Station, or a Ministry of Agriculture Experimental Husbandry Farm, designed primarily for fieldwork on irrigation. The Meteorological Research Committee of the Air Ministry should be encouraged to initiate or accelerate research on quantitative forecasting of rainfall for periods of three to four days ahead.

6. Irrigation users should have adequate representation on any water controlling authority.

APPENDIX A

PERIOD DURING WHICH IRRIGATION IS MOST LIKELY TO BE NEEDED FOR DIFFERENT CROPS TO AVOID APPRECIABLE YIELD REDUCTION IF PREVIOUS MONTH'S RAINFALL HAS BEEN BELOW AVERAGE

Note: This table is NOT a guide for irrigating crops. It is intended to indicate in which months a demand for water or equipment may occur.

—————Supported by experimental evidence.

.....Practical experience.

	J	F	M	A	M	J	J	A	S	O	N	D
Beans												
Runner												
Broad												
Brussel Sprouts												
Cabbage												
Summer												
Spring												
Carrots												
Early												
Maincrop												
Cauliflower												
E. Summer												
Autumn												
Winter (broccoli)												
Celery (Self-blanching) ..												
Kale												
Leeks												
Lettuce												
Early planted												
Summer planted												
Late summer sown												
Onions												
Salad												
Maincrop												
Radish												
Turnip (bunching)												
Cereals												
Winter												
Spring												

	J	F	M	A	M	J	J	A	S	O	N	D
Peas							*					
Potatoes												
Early												
Maincrop												
Sugar beet												
Apples						*	*					
Blackcurrants												
Cherries						**						
Pears							**					
Plums							**					
Raspberries												
Strawberries												
Grass												

*Usually a succession of sowings.

**July is a peak period for irrigation need generally; if tree fruits on deep soils are well watered in June, they may be able to pass July without further demand, so freeing the irrigation supply for other crops.

Note: Some of the early requirements (March and April) are primarily to improve conditions for cultivation.

APPENDIX B

ACREAGES LIKELY TO BE IRRIGATED

For certain crops such as potatoes and sugar beet, demand is inelastic and there are already embarrassing surpluses in some years; with others such as some fruits and some vegetables, demand is at present elastic. In attempting to predict the areas likely to be irrigated this economic factor as well as the other factors has also to be considered.

A. POTATOES

1. *Maincrop potatoes*

At the present time the national limit is 800 000 acres; each farmer has a given allocation and it is the practice of the Marketing Boards to announce a year ahead the percentage of the allocated acreage that may be grown, e.g. 90 per cent. The aim of the Board is to ensure that, in the driest year, sufficient potatoes will be produced. Irrigation should ease their task by stabilizing yields and reducing the total acreage necessary. Not all the crop can profitably be irrigated; about 20 per cent is grown outside the irrigable area, and many of the plots within the irrigable area are too small to justify the purchase of irrigation equipment.

	<i>Acres</i>
Total area of main crop in 1959	470 000
" " " " " " within the irrigable area	380 000
Less area grown in plots of 10 acres or less	100 000
Estimated irrigable area	280 000

Irrigation will increase the yield of this acreage on average by 40 per cent; so if the total production is to remain constant, the total acreage must be reduced proportionally. The total irrigable acreage will then fall to 230 000 acres.

2. *Early potatoes*

Here the problem is more complicated; increased use of irrigation equipment by providing protection against frost may not only increase the yield but also enable an earlier and more valuable market to be captured. Of the total area of 95 000 acres, about 20 000 are outside the irrigable area and almost the whole of the remainder could be irrigated. The increased yield would, however, probably reduce the demand for maincrop potatoes but no reduction in the main crop acreage concomitant upon this has been attempted.

B. SUGAR BEET

The total amount of sugar that can be produced in this country is restricted by international agreement. Increased yields per acre, therefore, will lead to a decrease in area.

Sugar beet only responds economically on soils with low moisture reserves: three-quarters of the crop within the irrigable area is grown in Lincolnshire, Norfolk and Suffolk and in these areas half the crop is grown on soils unsuitable for irrigation; this sample is assumed to be typical. Irrigation is expected to increase the yield of the remaining area by 25 per cent so that if the total production is to remain constant, the total acreage must be reduced proportionally. The total irrigable area will thus be 190 000 acres.

C. GRASSLAND

It is unlikely to be economic to irrigate grassland unless it is intensively utilised, probably through a dairy herd in the form of milk. Moreover, irrigation is unlikely to

be economic on dairy farms with fewer than 15 cows because of labour and management problems. It is estimated that within the area under consideration, there are 1½ million cows in herds of more than 15 cows. Allowing half an acre of irrigated grass per cow, an estimate of 750 000 acres is obtained.

D. VEGETABLES

Water is used for watering-in plants and rewetting soils before sowing, as well as intensively irrigating the responsive crops. The crops which are likely to be intensively irrigated are:

<i>Crop</i>			<i>Part Irrigated</i>					<i>Acreage</i>
Peas	..	..	Green for market	..	..	..	..	65 000
			For canning and quick freezing					
			For drying					
Broad beans	..	..	Broad beans—half	..	..	..	..	20 000
			(half the crop will be mature before the soil moisture deficit occurs)					
Runner beans	..	..	All	..	..	..	..	10 000
Dwarf beans	..	..	One quarter	..	..	..	..	8 000
Summer cabbage	..	..	All	..	..	..	..	9 900
Summer cauliflower	..	..	All	..	..	..	..	6 500
Lettuce	..	..	All	..	..	..	..	8 000
Self-blanching celery	..	..	All	..	..	..	..	4 000
Carrots:								
for bunching	..	..	All	..	..	..	..	6 500
main crop	..	..	Half	..	..	..	..	16 000
								150 000

E. FRUIT

The total area of tree fruits is about 240 000 acres. Not all of this will require irrigation. Some is in farm orchards, not intensively managed; some on deep soil, not requiring irrigation and some too far from water sources. It is estimated that irrigation may be required and practicable on about one-fifth of the total tree fruit area. This will include a higher percentage in the south and east and a lower percentage in the west. The area of small fruits is about 40 000 acres. The demand for irrigation of these may well be greater, and about two-fifths of the acreage may be irrigated, giving a total area of 61 000 acres.

APPENDIX C

PROBLEMS FOR FURTHER STUDY

Subjects on which it is considered that further study is still required are listed below, together with the order of priority assigned to them. Research is, in fact, being pursued vigorously on a number of the major problems on this list.

Note on Priorities:

- A. Sufficiently important to justify extra men, money and materials being made available now.
- B. Sufficiently important to be taken into existing research programmes (or new programmes started under A) as soon as A projects are under way.
- C. To be taken up when possible, perhaps leaving the initiative to workers in other fields, e.g. problem A(2) might be part of a fertilizer experiment with irrigation as a variable.

A. CHEMICAL PROBLEMS	PRIORITY
(1) Effects of impurities and pollutants (e.g. sewage, trade effluents, brackish water) in irrigation water	B
(2) Effects of applying fertilizers, insecticides, fungicides and other substances in irrigation water	C
(3) Effects of irrigation on utilization by different crops of	C
(a) normal plant nutrients	
(b) trace elements	
 B. PHYSICAL PROBLEMS	
(1) Effects of quantity, speeds and rate of application upon soil structure including	B
(a) chemicals added to water	C
(b) impurities	
(c) pollutants	
(2) Effect of soil type and cultural practices on the availability of water to plants	B
(3) Effects of additives on soil structure	C
 C. METEOROLOGICAL PROBLEM	
(1) Forecasting	A
 D. ENGINEERING	
(1) Water conservation and supply problems:	
Location and amount of present and future irrigation demands	A
Methods of supply on an area and a local basis	A
Organization, co-ordination and control of water	
Surface storage possibilities	
Artificial recharge	
Transfer of water from higher rainfall areas	



	PRIORITY
Design details and construction standards for small reservoirs..	A
Measurement of discharges from small catchments	
Desirable standards for site investigation	
Earthworks standards	
Inlet, outlet and overflow works	
The need for lining	
Methods of lining	
Methods of water demineralization	C
(2) Design of equipment, including efficiency of sprinkler systems, and sprinkler heads for frost protection	B
(3) Time and motion studies on the most efficient use of equipment and the most efficient equipment	B
E. BIOLOGICAL PROBLEMS	
(1) Interaction of soil structure changes and plant growth	B
(2) Effect on healthy farm crops and livestock of pathogens in polluted water	B
(3) Effects of variations in quantity and quality of water supply upon soil flora and fauna	C
(4) Effects upon diseases and pests and their control.. .. .	C
(5) Effects on the micro-environment of plants	C
(6) Effect of possible contamination of crops with organisms pathogenic to man which may be carried in polluted water	C
F. PLANT PHYSIOLOGY	
(1) Water requirements of different crops	A
(2) Effects upon quality, flavour, texture, colour, shape and keeping quality of all crops, but especially fruit and vegetables	A
(3) Effects on crop growth, development, yield, quality and keeping quality of varying moisture supplies at different stages of each crop cycle	A
(4) Investigations into functioning of root systems	A
(5) Study of depth and distribution of rooting systems of different crops	B
(6) To ascertain early symptoms of water shortage in crops	C
(7) Effects of temperatures of water and air at the time of irrigating on various crops	C
(8) Morphological effects of irrigation on plants (physical damage)	C
(9) Need for breeding varieties with low water requirements	C
G. HUSBANDRY	
(1) Effects of levels of irrigation on crop yields in relation to soil types	A
(2) Interactions of irrigation with fertilizers and spacing	A
(3) Effects on health of stock fed on irrigated crops with special reference to bloat, scouring and internal parasites	B
H. ECONOMICS	
(1) Priority for irrigating various crops when water is in limited supply	A
(2) Effect on profitability of crop and animal production	A
(3) Frequency of usage to make purchase of equipment and other capital expenditure worthwhile	C

OFFICE OF THE MINISTER FOR SCIENCE

Irrigation in Great Britain

A Report by the Natural Resources
(Technical) Committee

CORRECTION

Page iii: *for* "NATIONAL RESOURCES (TECHNICAL)
COMMITTEE"

read "NATURAL RESOURCES (TECHNICAL)
COMMITTEE"

LONDON

HER MAJESTY'S STATIONERY OFFICE

1962

